

# The annual cycle of circulation in the southwest subtropical Pacific

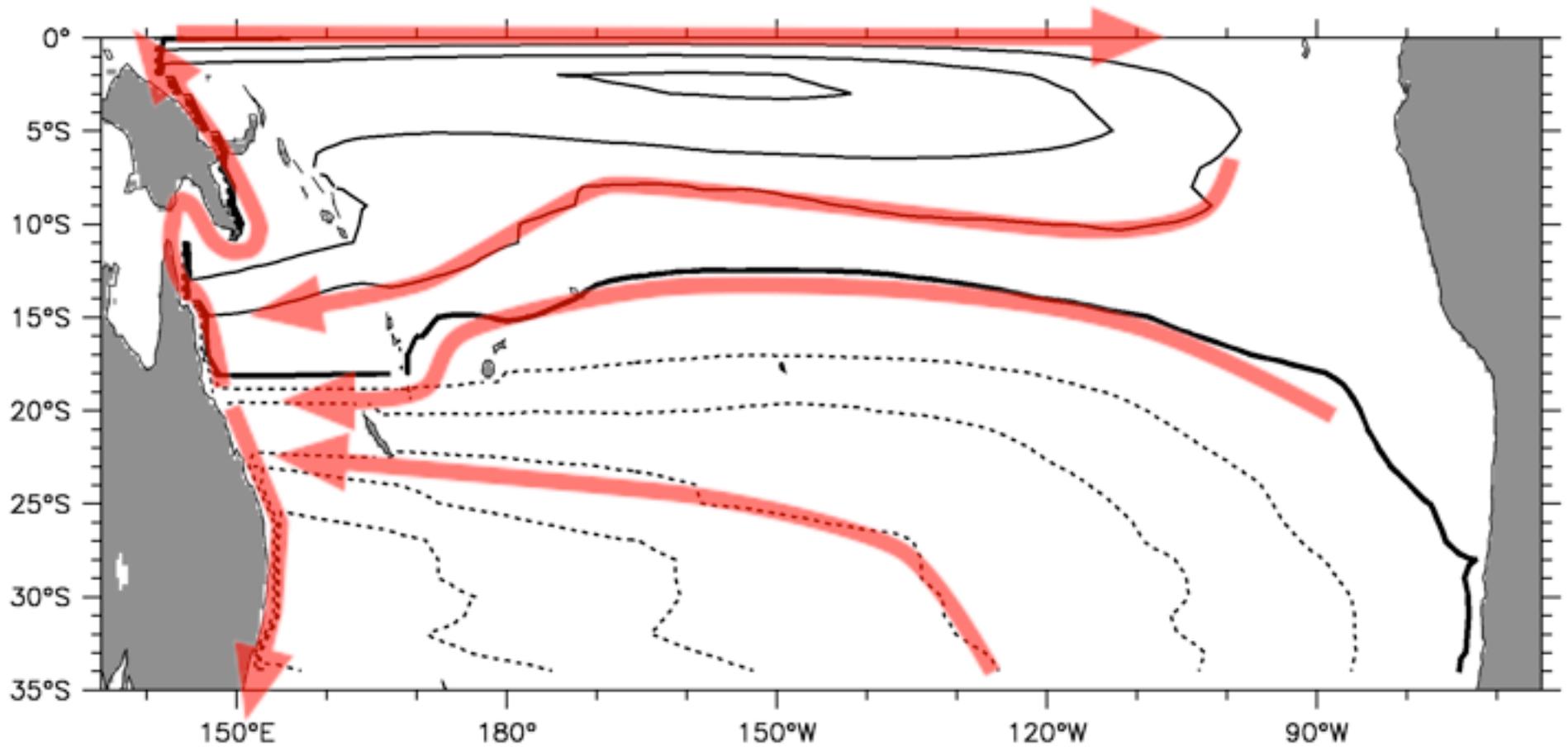
William S. Kessler and Lionel Gourdeau

(Manuscript accepted by JPO)

- We are interested in the southwestern Pacific because of its position athwart a major pathway from the subtropics to the equator:  
How are water masses redistributed at the western boundary?
- It is likely that interannual and decadal variability is most climatically important, but here we take a first step by looking at the annual cycle.
- In the absence of observations sufficient to diagnose the variability, we analyze an ocean GCM (OPA/ORCA).

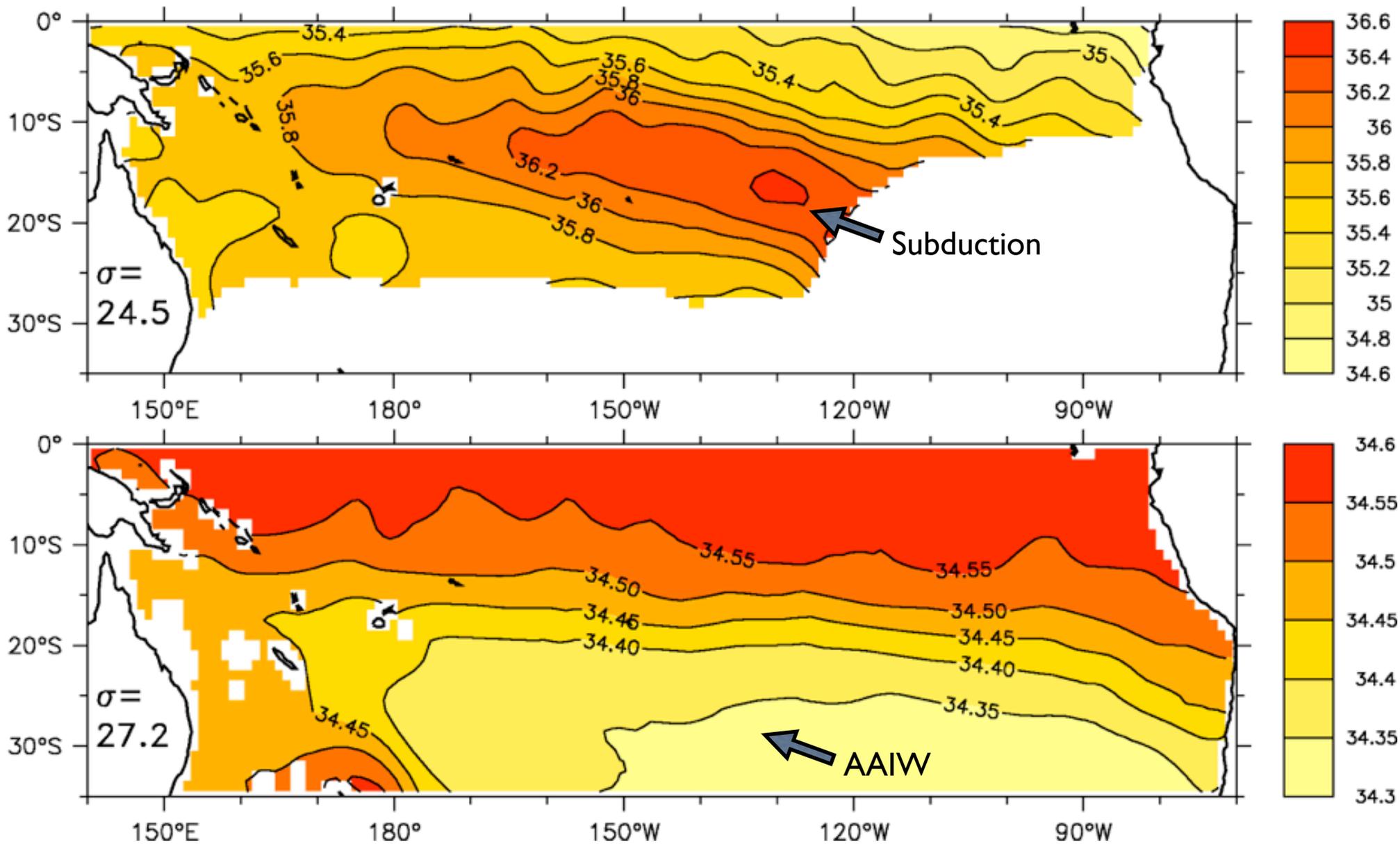
# The big picture: Redistribution of mass at the western boundary

Island Rule (Sverdrup) streamfunction (ERS winds)

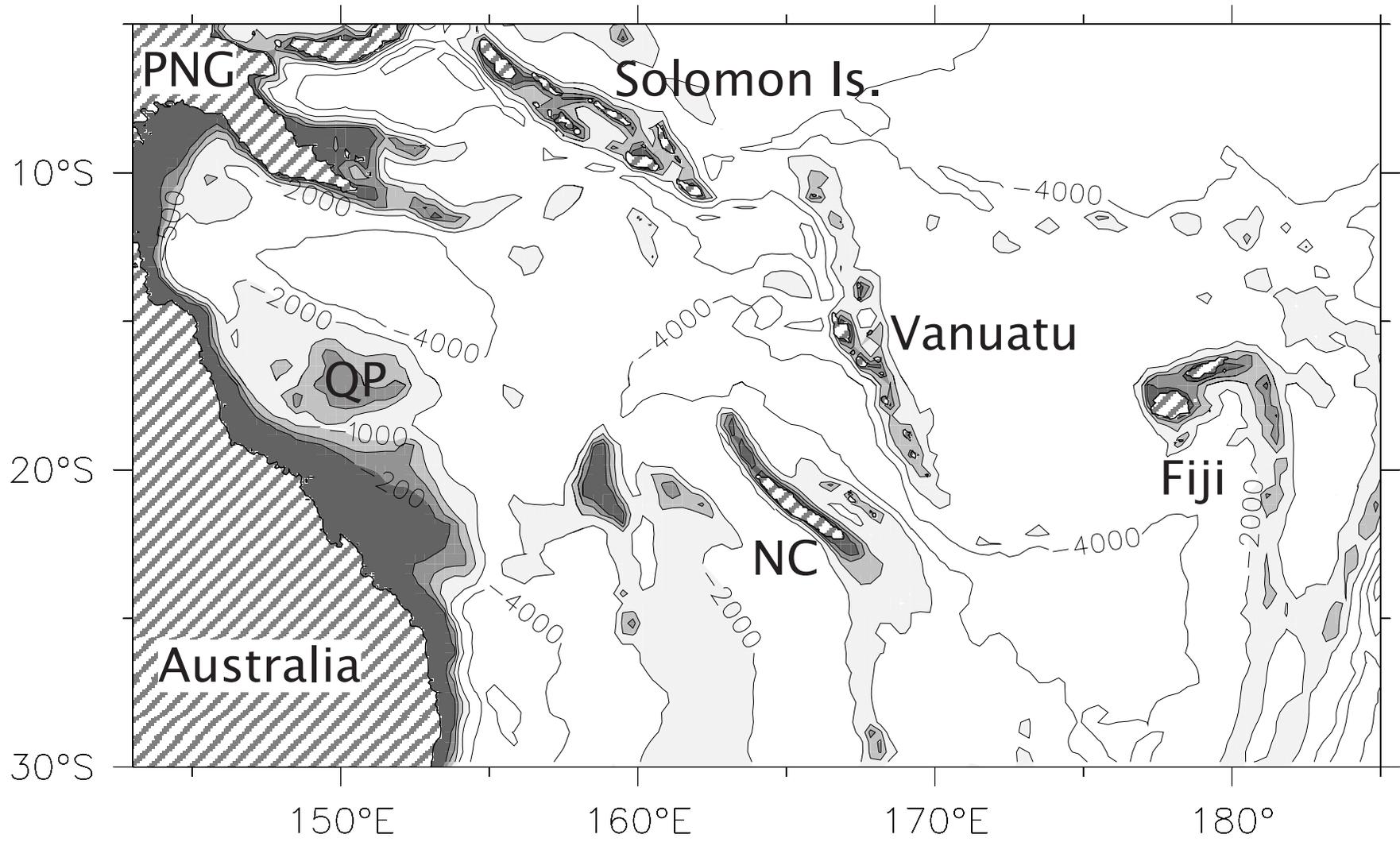


# Water mass redistribution in the SW subtropical Pacific

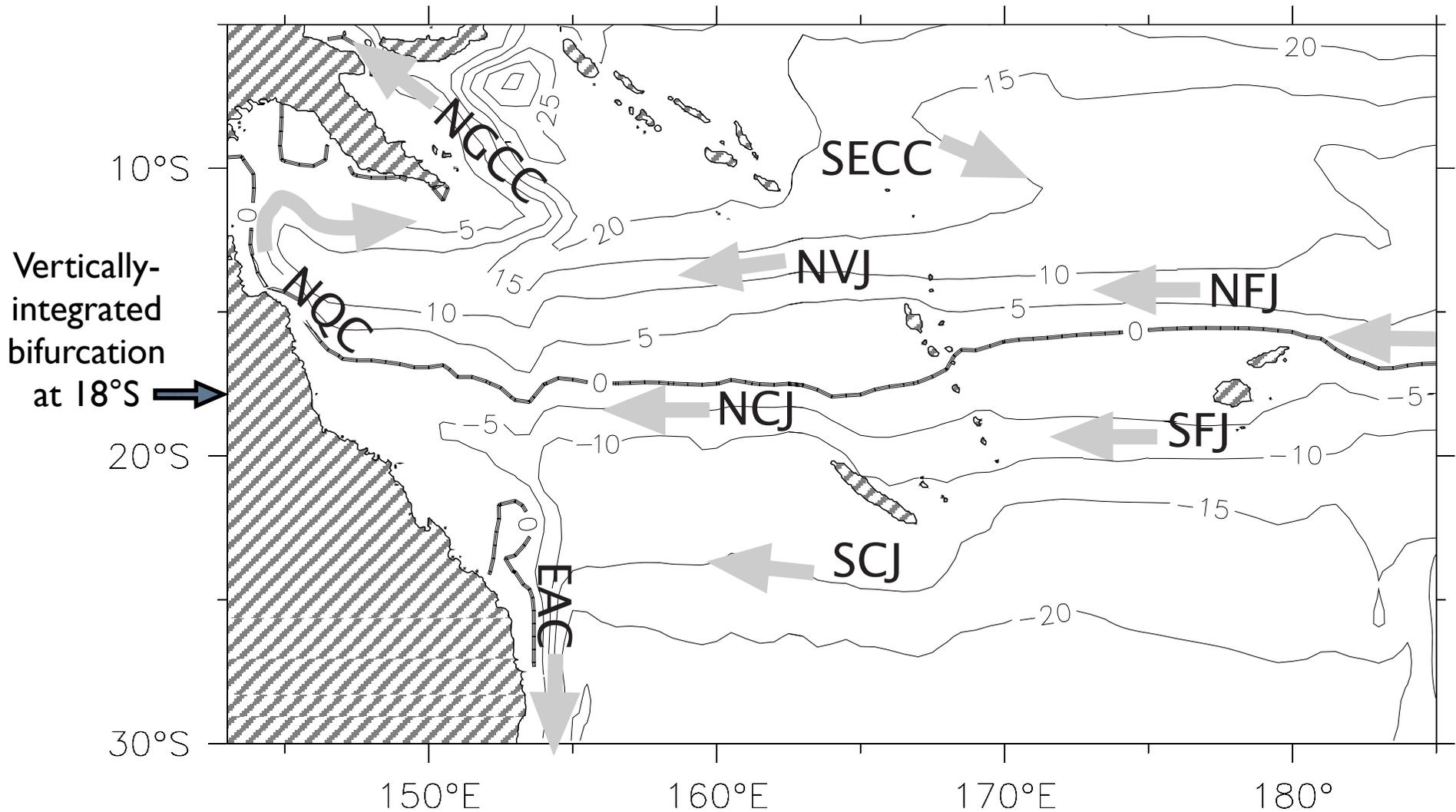
Salinity on isopycnals 24.5 and 27.2 (Levitus)



# Bathymetry of the SW subtropical Pacific



# ORCA model streamfunction



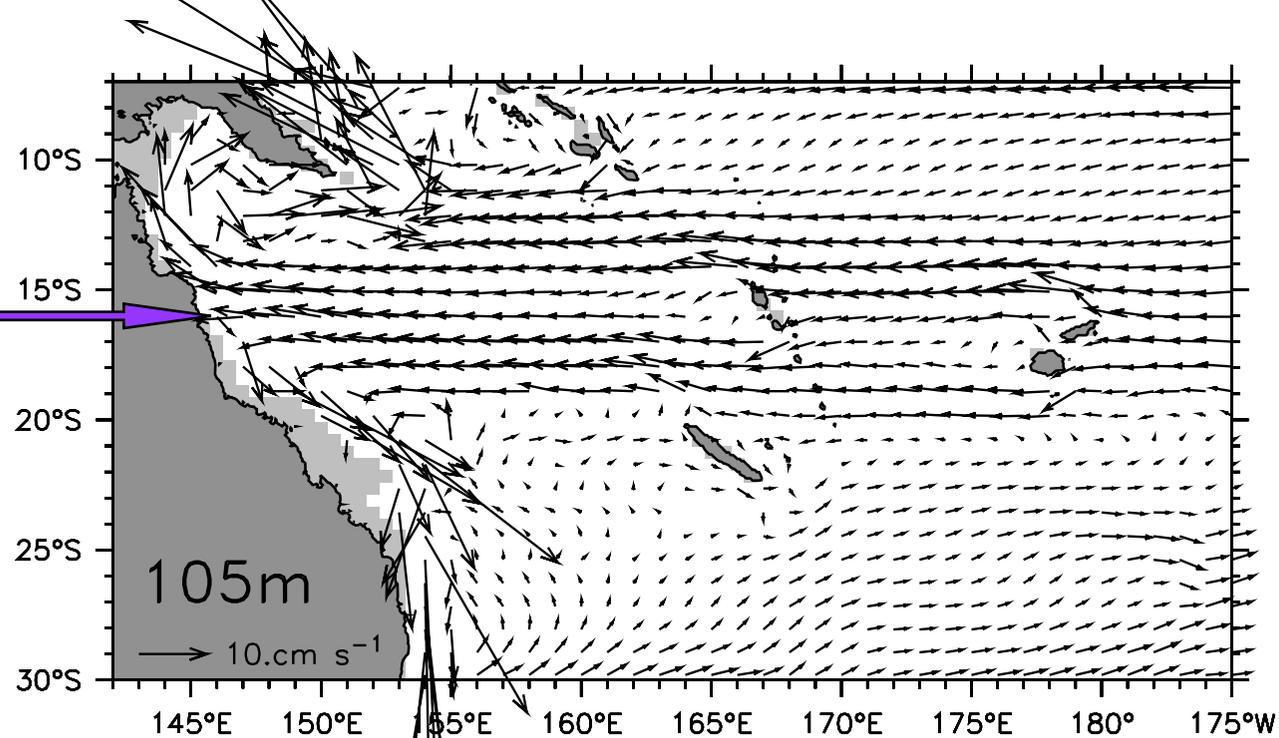
Western Boundary Currents  
EAC = East Australian Current  
NQC = North Queensland Current  
NGCC = New Guinea Coastal Current

SECC = South Equatorial Countercurrent  
N, SFJ = North, South Fiji Jet  
NVJ = North Vanuatu Jet  
N, SCJ = North, South Caledonian Jet

Tilted gyre,  
tilted  
bifurcation

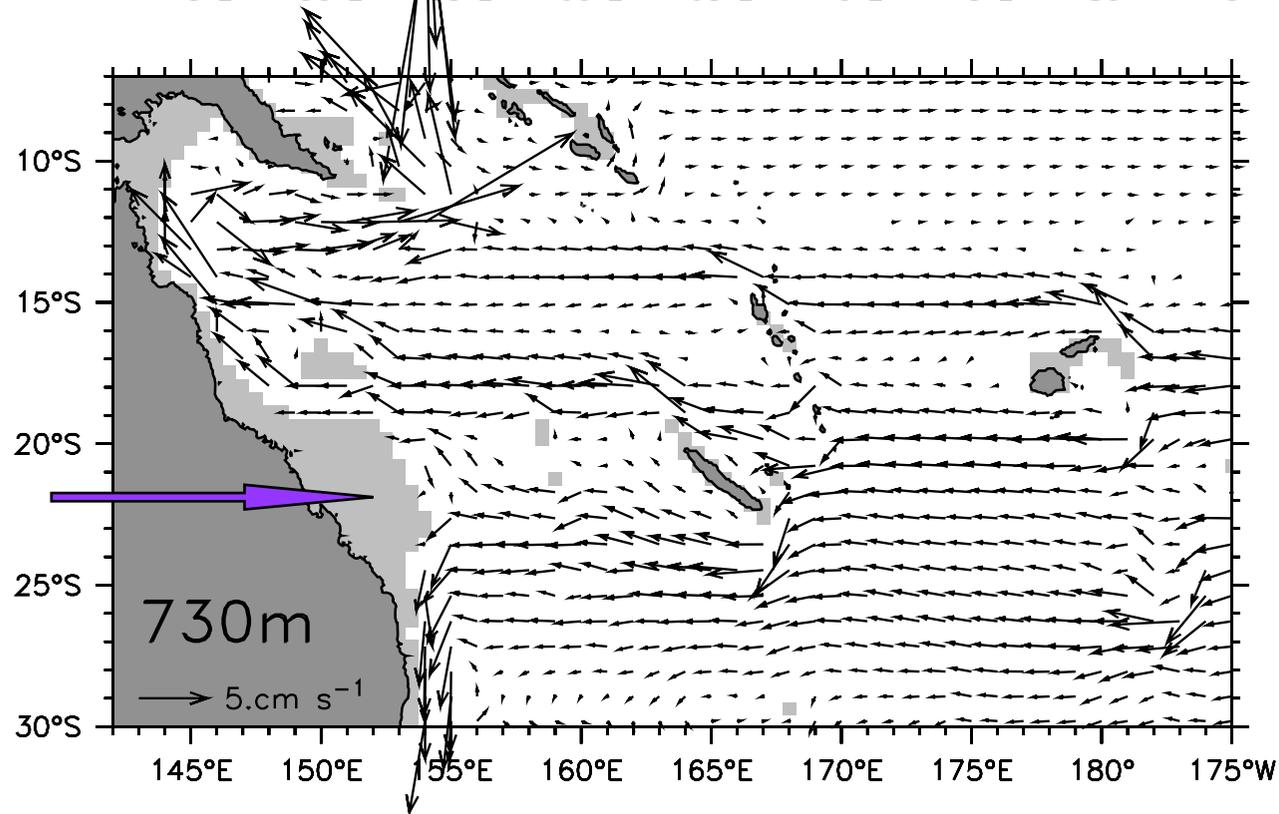
105m

Bifurcation at 16°S

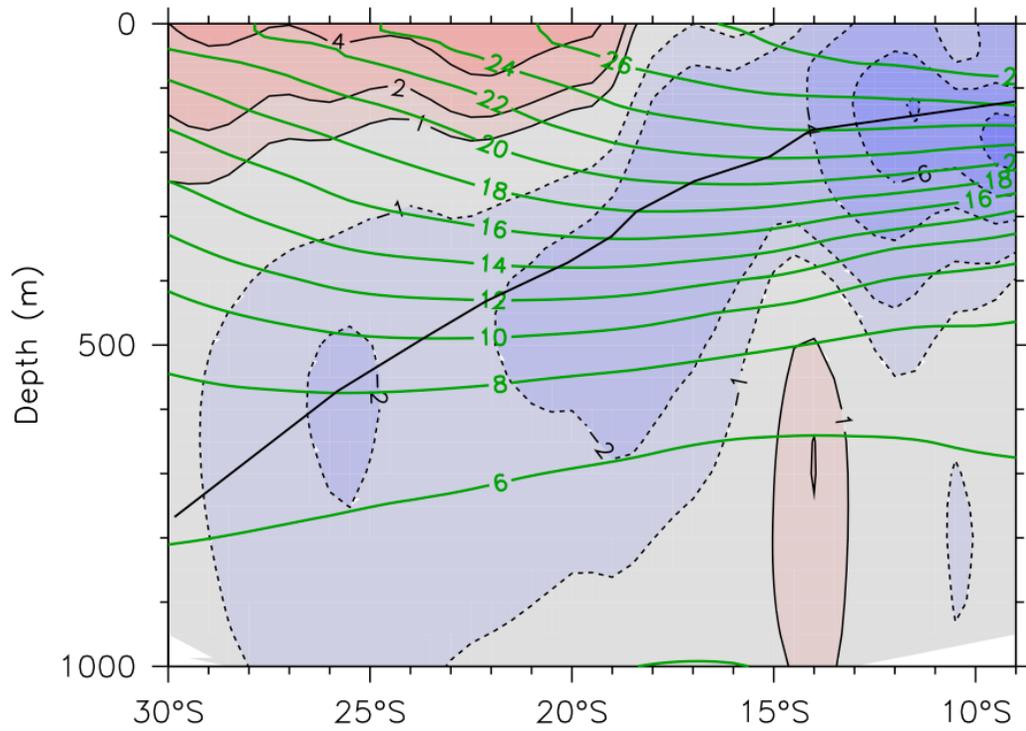


730m

Bifurcation at 22°S

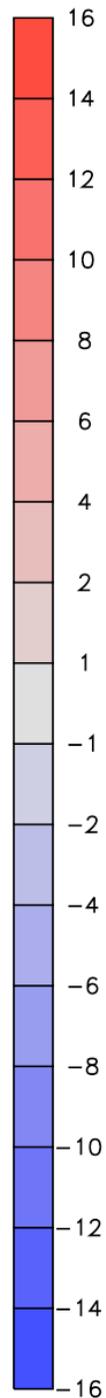
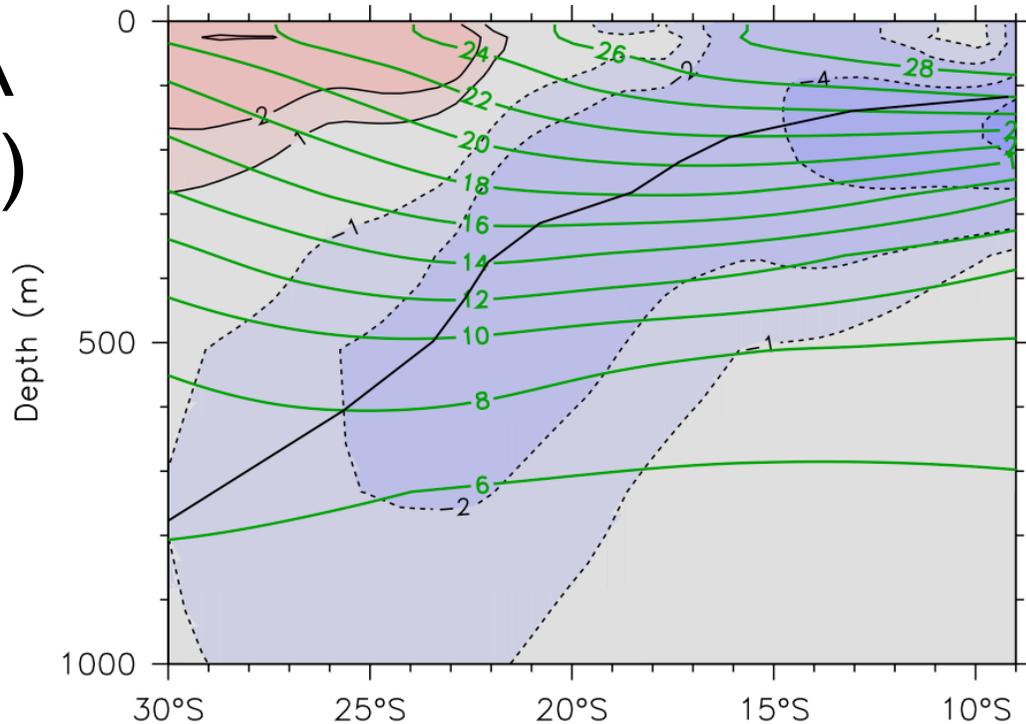


CARS  
(obs)



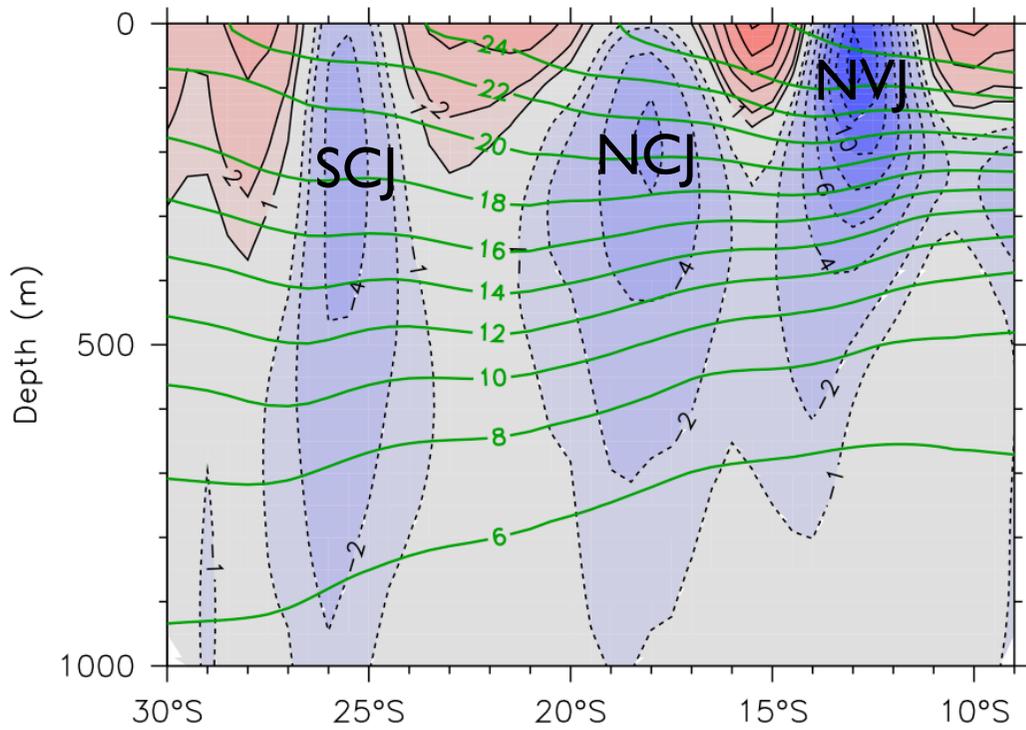
Zonal current  
and temperature  
at 175°W  
(east of islands)

ORCA  
(model)

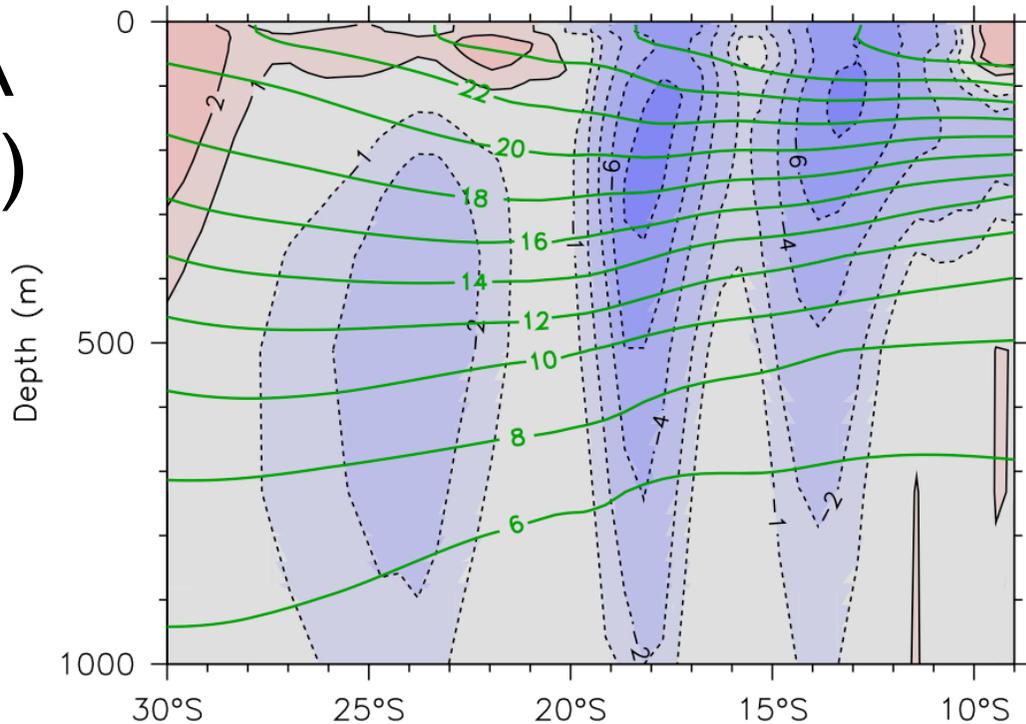


CARS is a new  
CSIRO CTD  
compilation for  
the S Pacific and  
S Indian Oceans  
Ridgway & Dunn (2003)

CARS  
(obs)



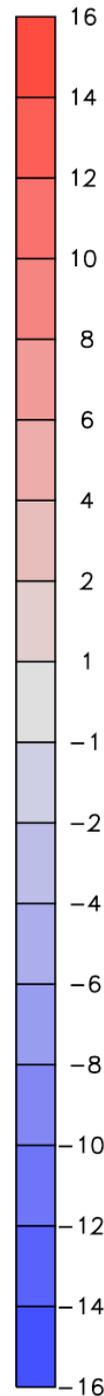
ORCA  
(model)



Zonal current  
and temperature  
at 162.5°E  
(west of N.C.)

The SEC is broken  
into distinct jets  
behind the islands.

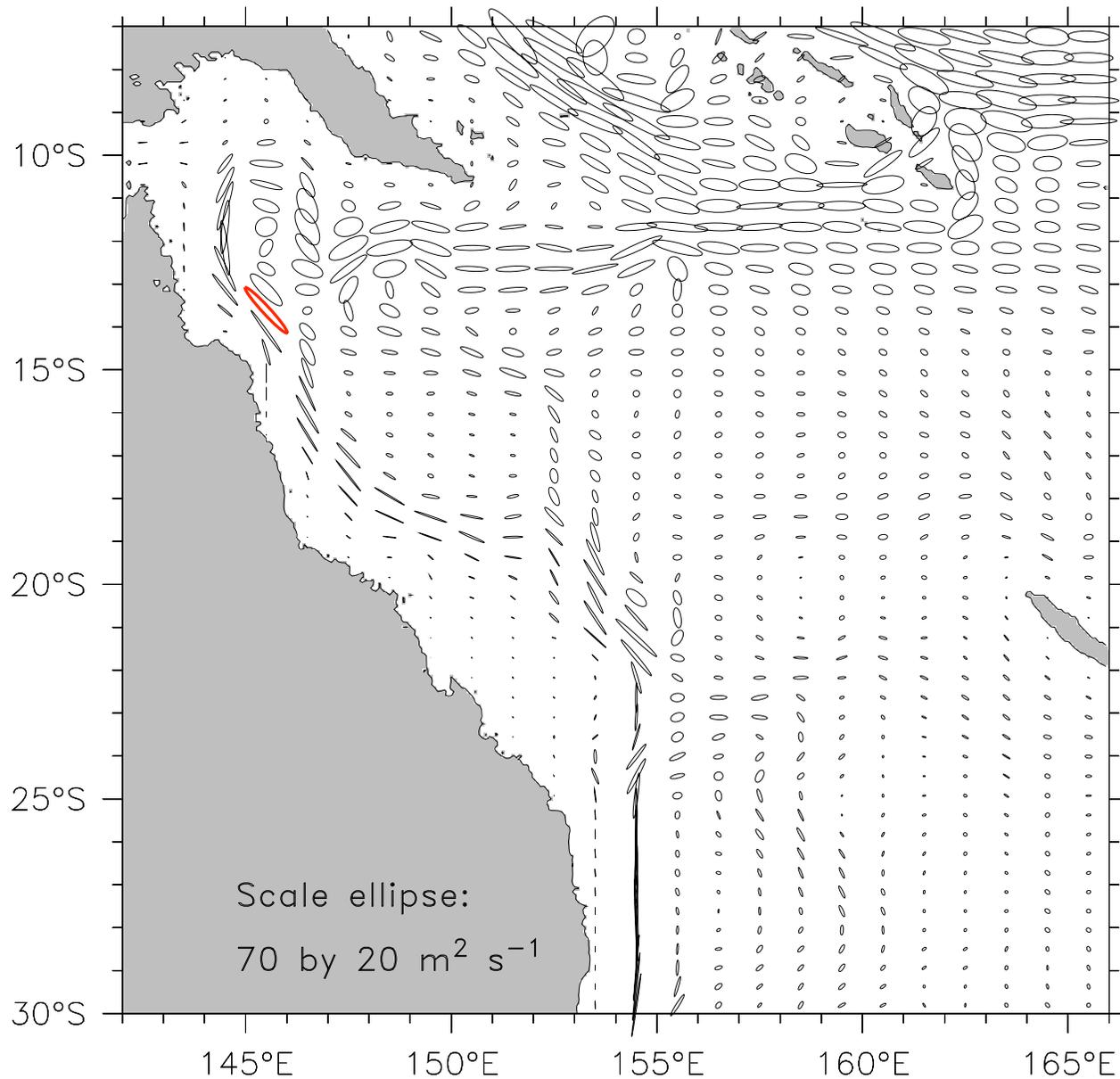
The jets have  
subsurface maxima.



## Summary of brief look at mean circulation

- Complex regional geometry/topography
- SEC divided into jets
- Tilted gyre (hence tilted bifurcation)
- Bifurcation/redistribution of SEC inflow
  - ⇒ Climate consequences?
  - ⇒ Implication that variations of the bifurcation produce transport anomalies to the equator

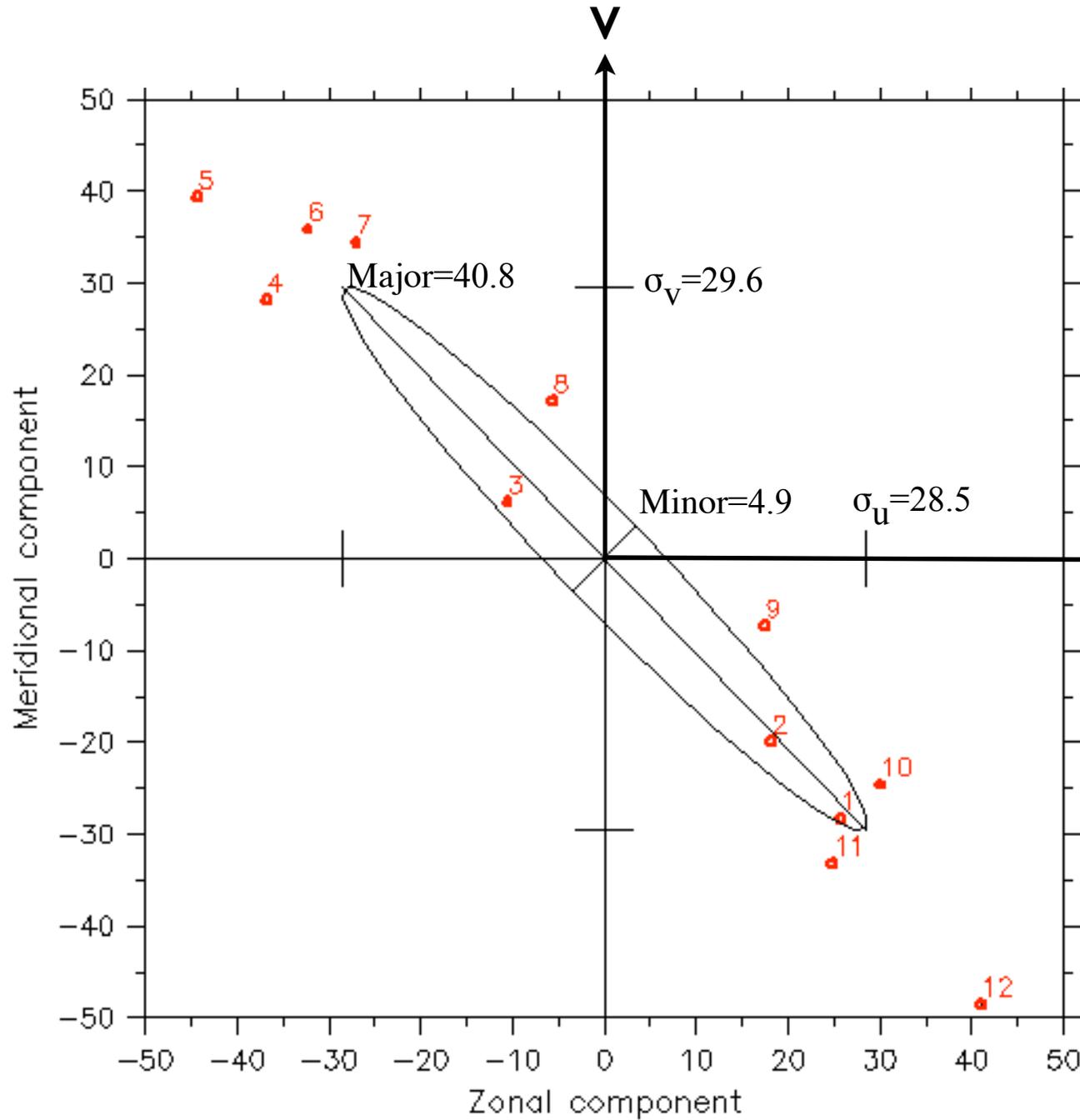
# Annual cycle transport variance ellipses



## 0-2060m transport

The major and minor axes of a variance ellipse are the standard deviations of the velocity components, *after the ellipse has been rotated to express the maximum possible variance in the major axis direction.*

# Variance ellipse at 13.6°S, 145.5°E

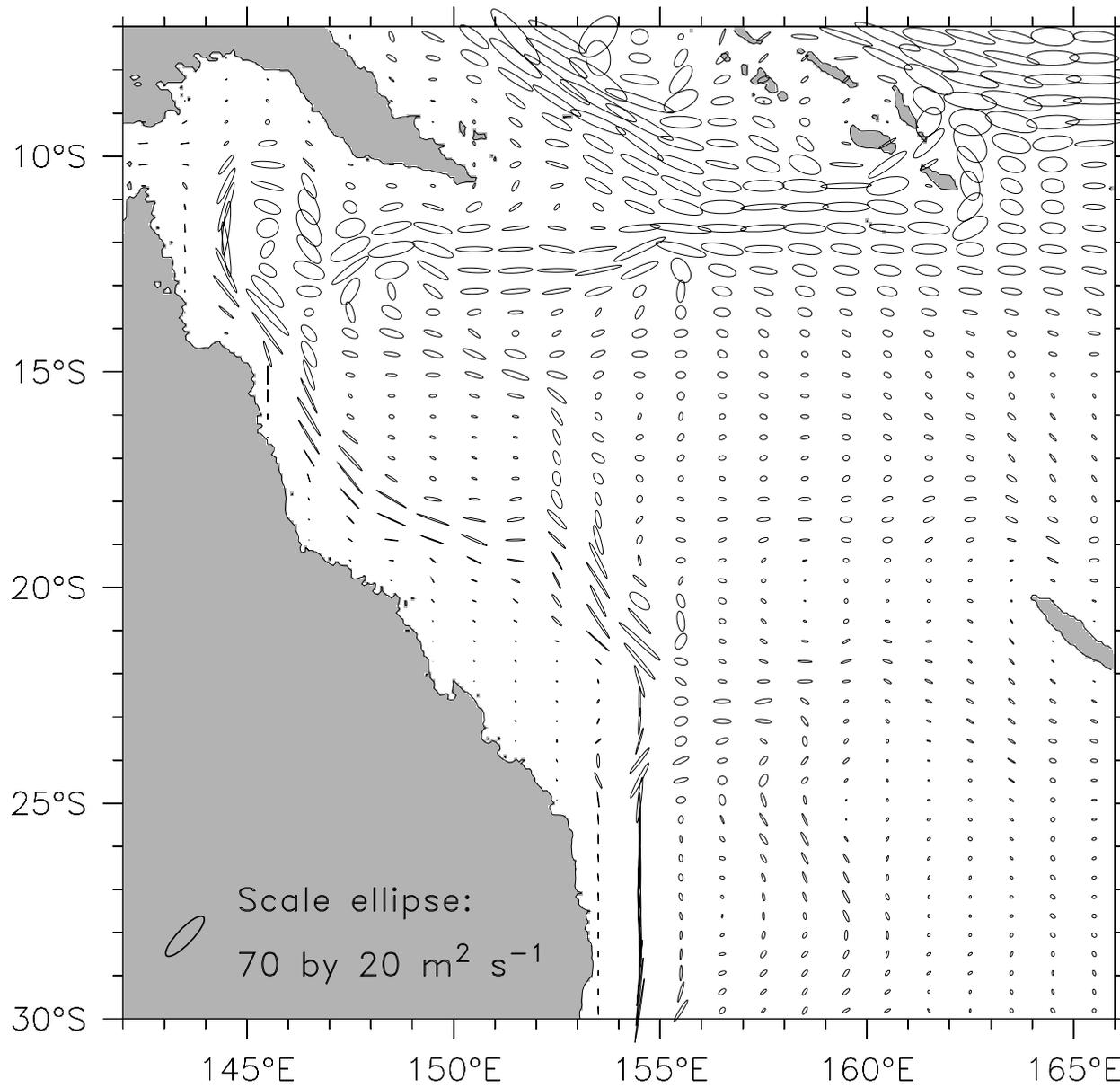


Red dots show monthly anomalies

At this location, 98% of the variance is expressed along the major axis.

(Units  $\text{m}^2 \text{s}^{-1}$ )

# Annual cycle transport variance ellipses



## 0-2060m transport

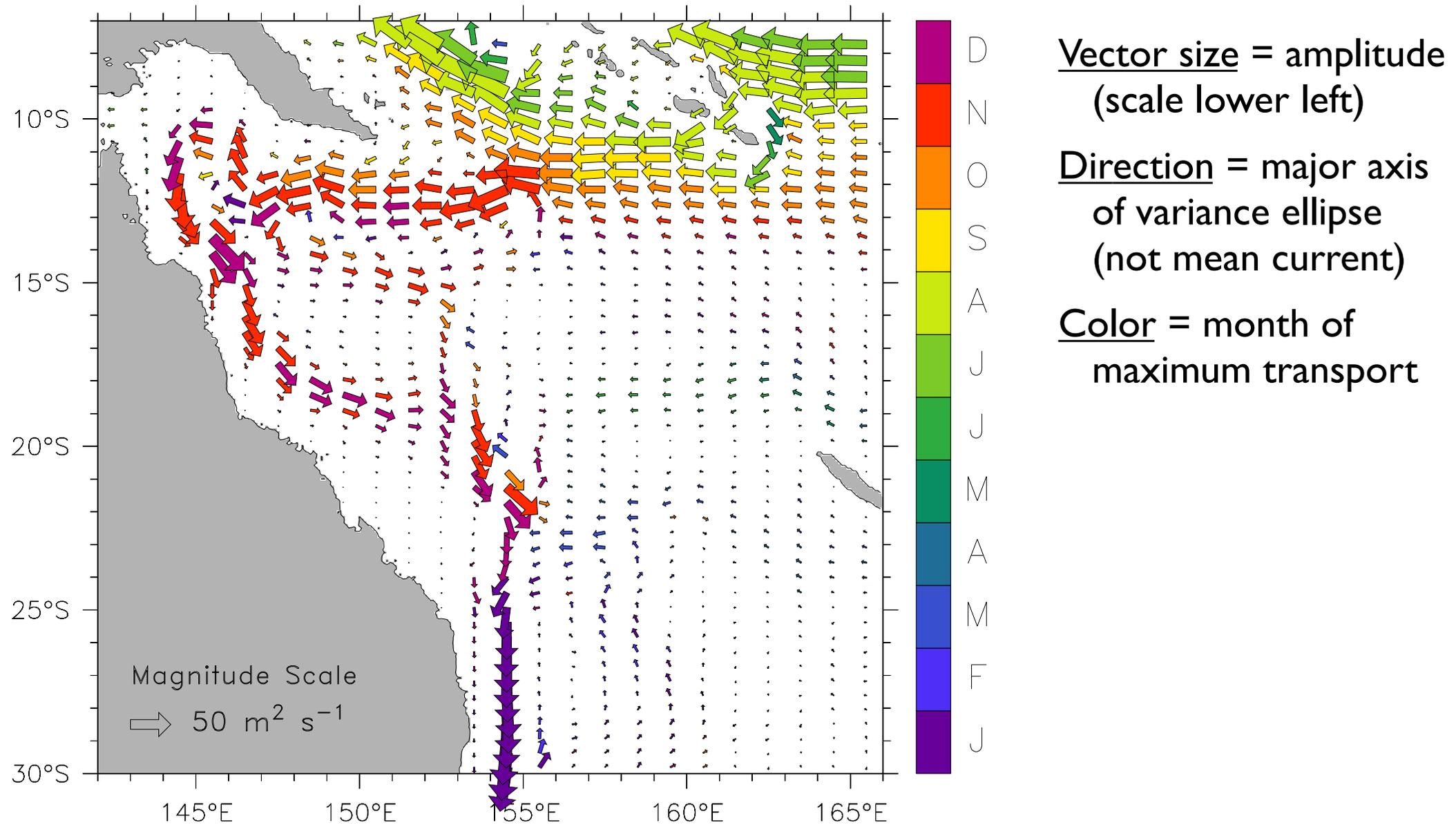
Small variability in the interior gyre.

Large-amplitude currents in the tropics and along the western boundary.

Elongated ellipses show 80-90+% of variance on the major axes, which are mostly aligned along the mean currents.

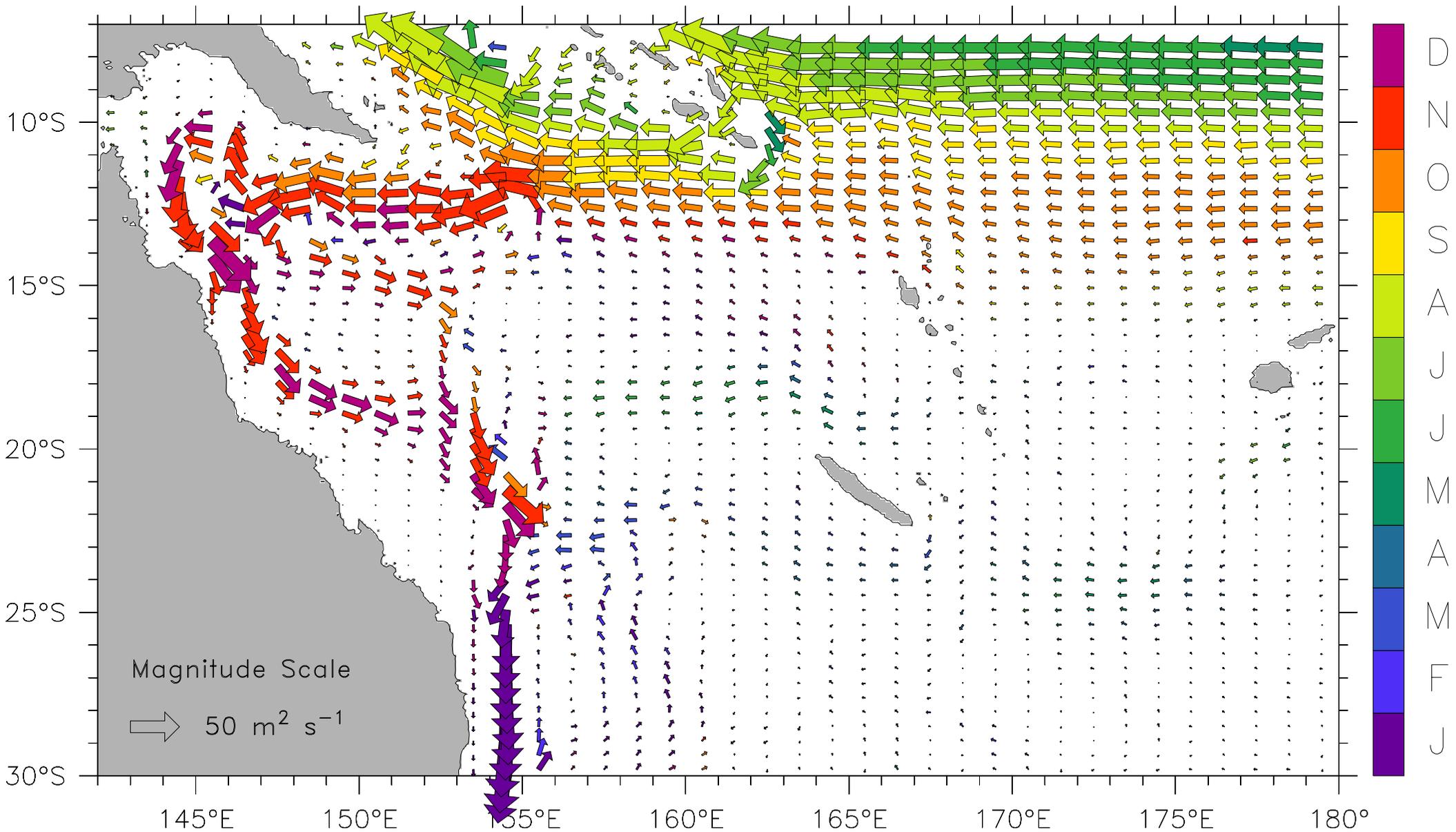
➡ Use the major axes to define a current-following coordinate.

# 1 cpy transport harmonic from variance ellipses

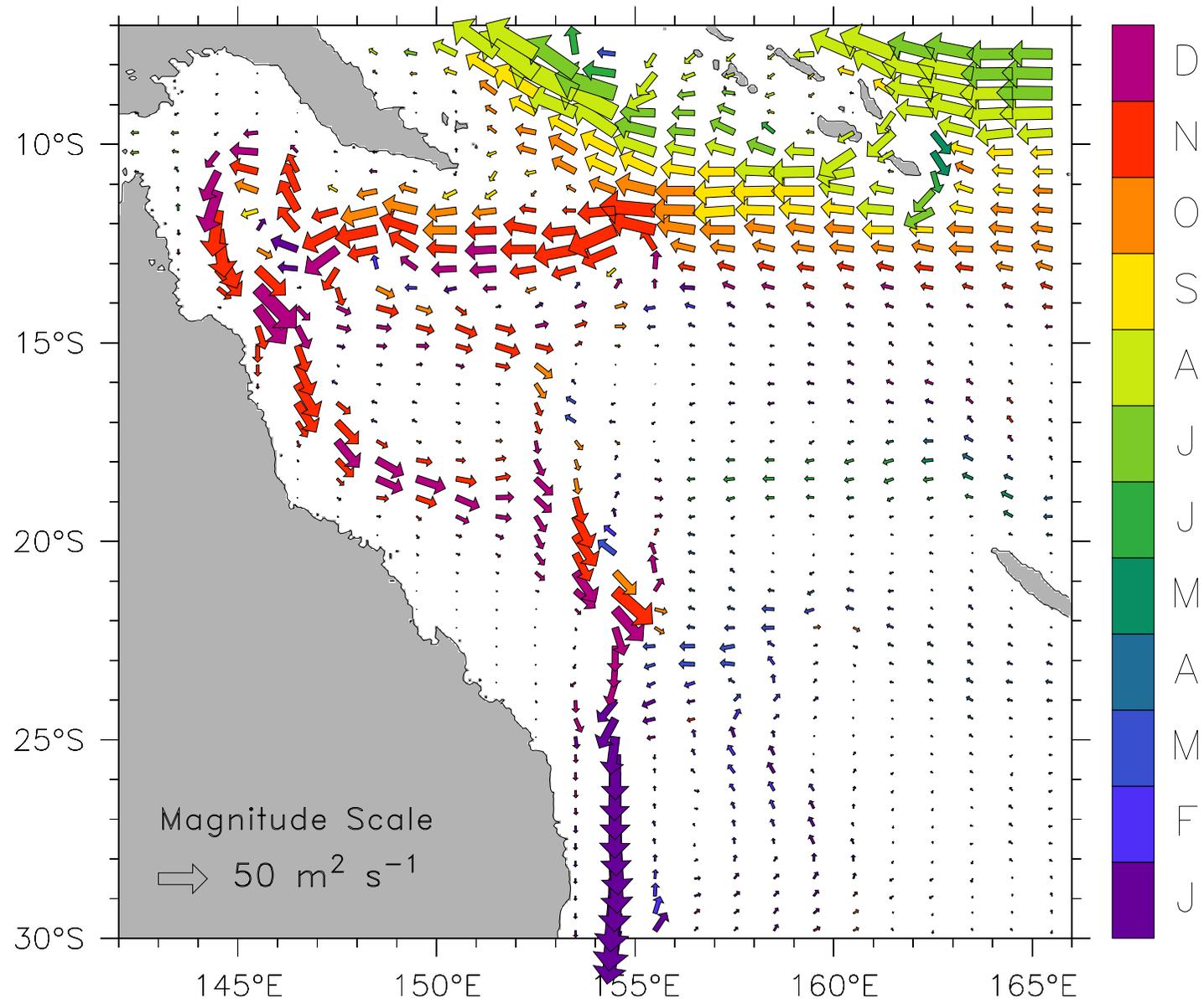


# The same pattern extends to the east

Little transport variance in the gyre center

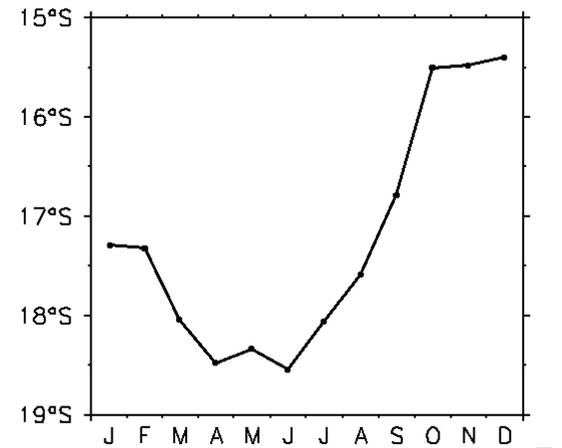


# Do subtropical WBC anomalies connect to the equator?



The WBC along the entire coast of Australia fluctuates coherently, while anomalies of the NGCC are nearly of the opposite phase.

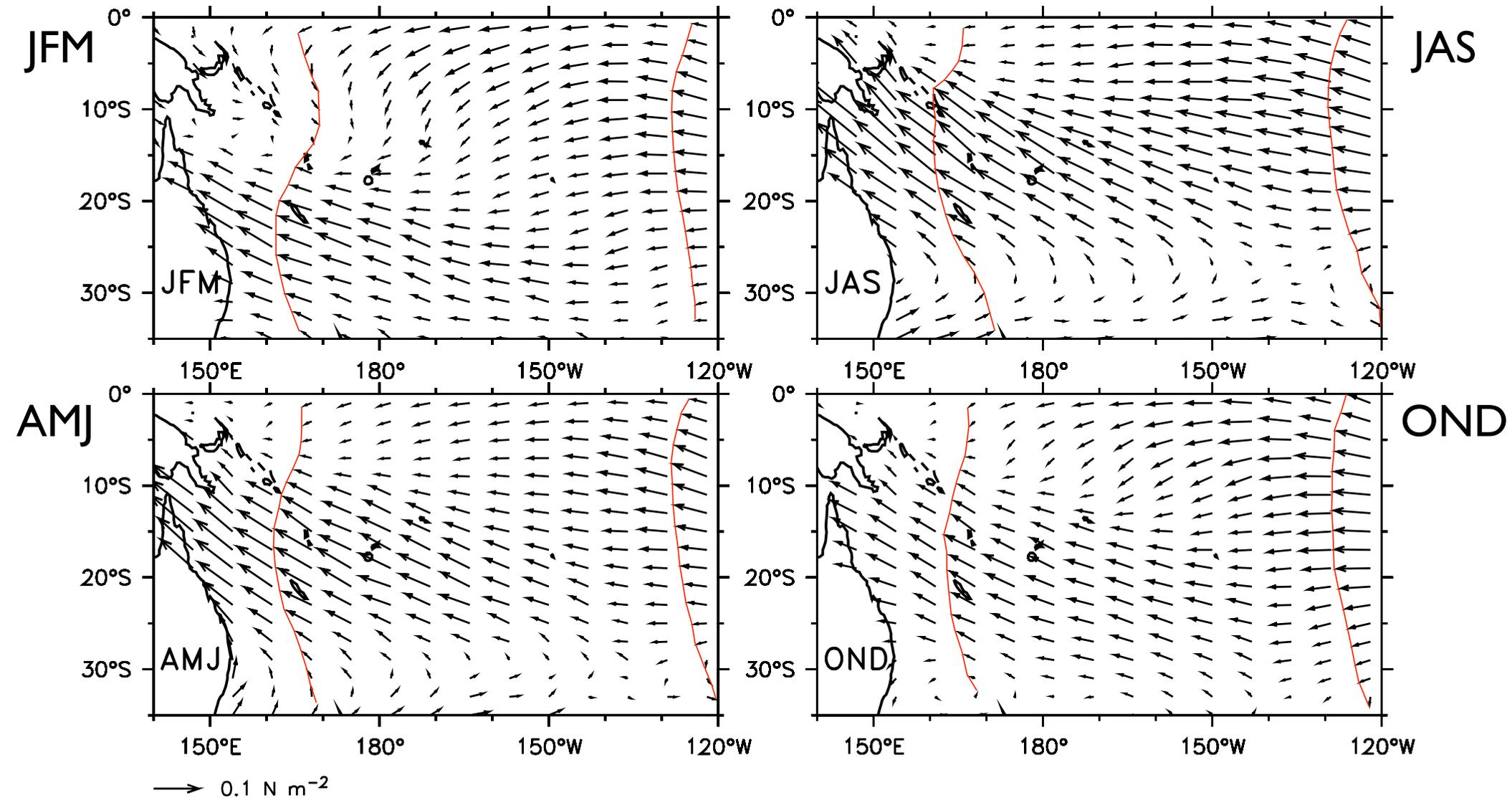
Bifurcation latitude



Annual coastal Australia WBC anomalies do not represent corresponding transports to the equator.

# Curl variations are much larger in the west

ERS wind climatology  
1991–2000



# The familiar reduced-gravity long Rossby wave model

$$\frac{\partial h}{\partial t} + c_r \frac{\partial h}{\partial x} + Rh = -\text{Curl} \left( \frac{\tau}{f\rho} \right), \quad c_r = -\beta \frac{c^2}{f^2}$$

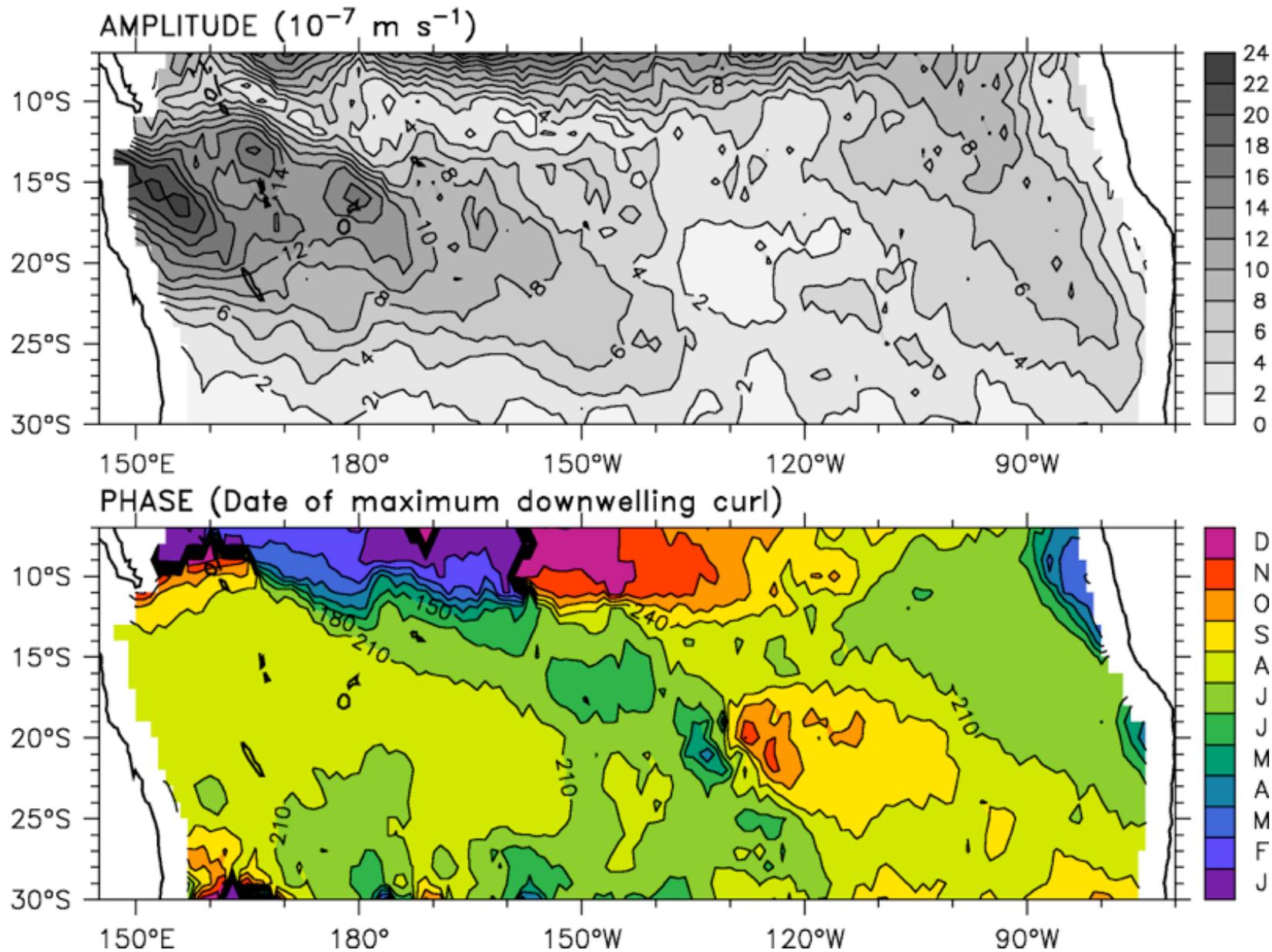
$h$  is the ULT anomaly,  $c$  is the Kelvin speed,  $R$  is a damping timescale,  $(2 \text{ yr})^{-1}$ .

The solution is found at each latitude independently:

$$h(x, t) = -\frac{1}{c_r} \int_{x_E}^x e^{-\frac{R}{c_r}(x-x')} \text{Curl} \left( \frac{\tau(x', t - \frac{x-x'}{c_r})}{f\rho} \right) dx'$$

The model is forced with an annual cycle of ERS winds (1991-2000), assuming no eastern boundary influence.

# 1 cpy harmonic of $Curl(\tau/f\rho)$



Equatorial-  
subtropical  
divide  
along 11°S

## Because the winds have a simple form ....

Chen and Qiu (2004) showed that for winds of the form: (a standing oscillation with uniform phase, decaying eastward)

$$Curl \left( \frac{\tau}{\rho f} \right) = B e^{i\omega t} e^{-(x-x_w)/L}$$

The Rossby solution is also a standing oscillation:

$$h(x, t) = \left( \frac{1}{i\omega - \frac{c_r}{L}} \right) Curl \left( \frac{\tau}{\rho f} \right)$$

which lags the Curl by  $\tan^{-1}(\omega L/c_r) = 2.5-3$  months:

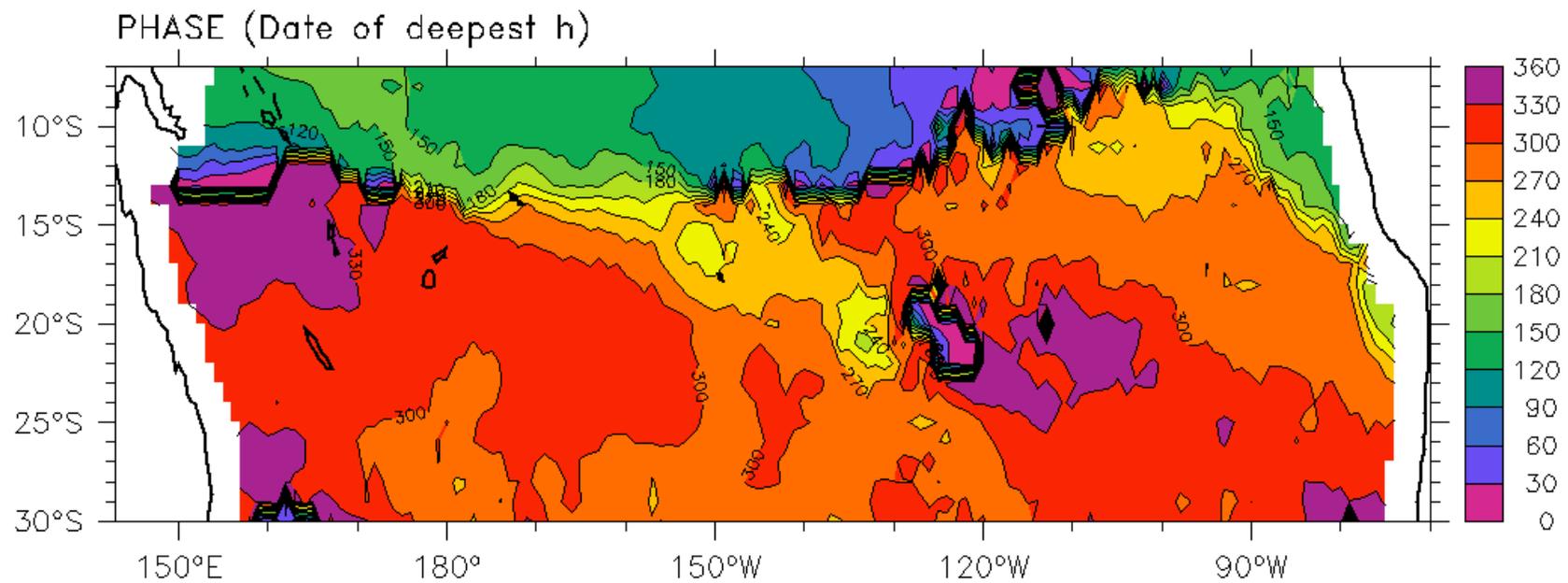
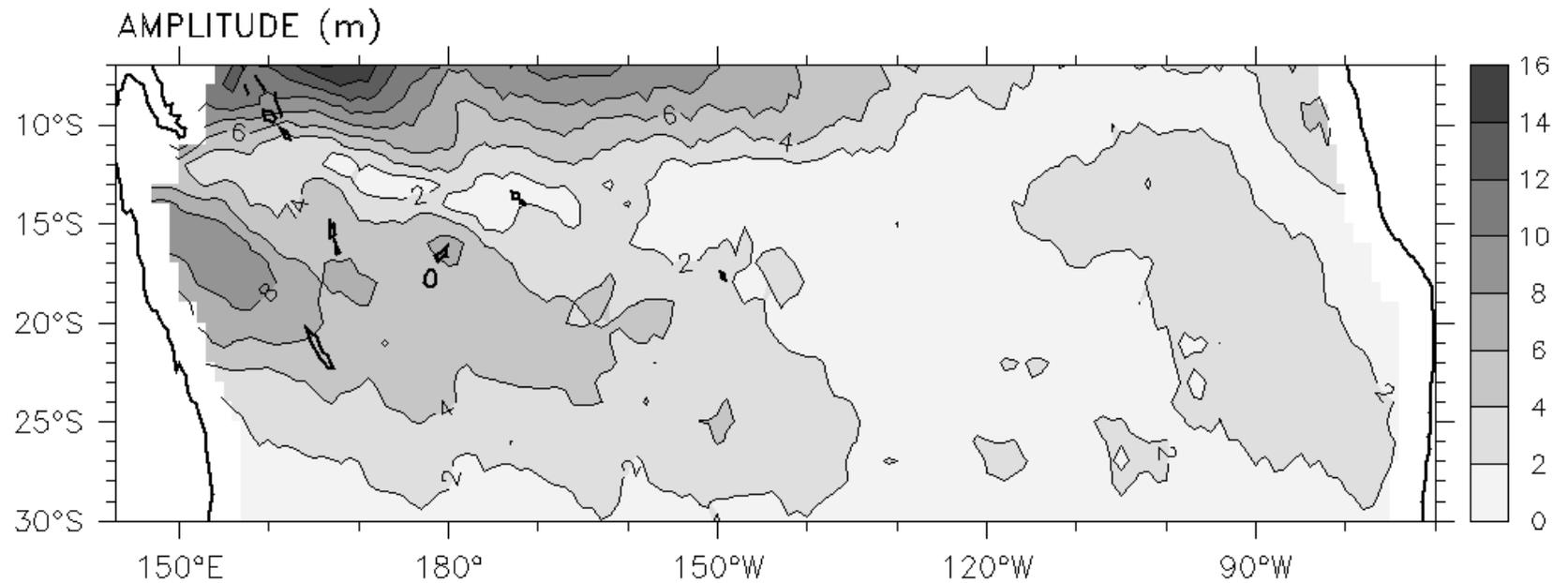
$$= - \left( 1 + i \frac{\omega L}{c_r} \right) \left( \frac{1}{\frac{\omega^2 L}{c_r} + \frac{c_r}{L}} \right) Curl \left( \frac{\tau}{\rho f} \right)$$

Phase lag                      Amplitude

- Propagating Rossby waves will not be apparent in this solution (will look a lot like Ekman pumping)
- Expect uniform phase (max h in Nov) and growing amplitude in the west

Rossby solution  $h$  implied by Chen/Qiu 04 form of wind forcing

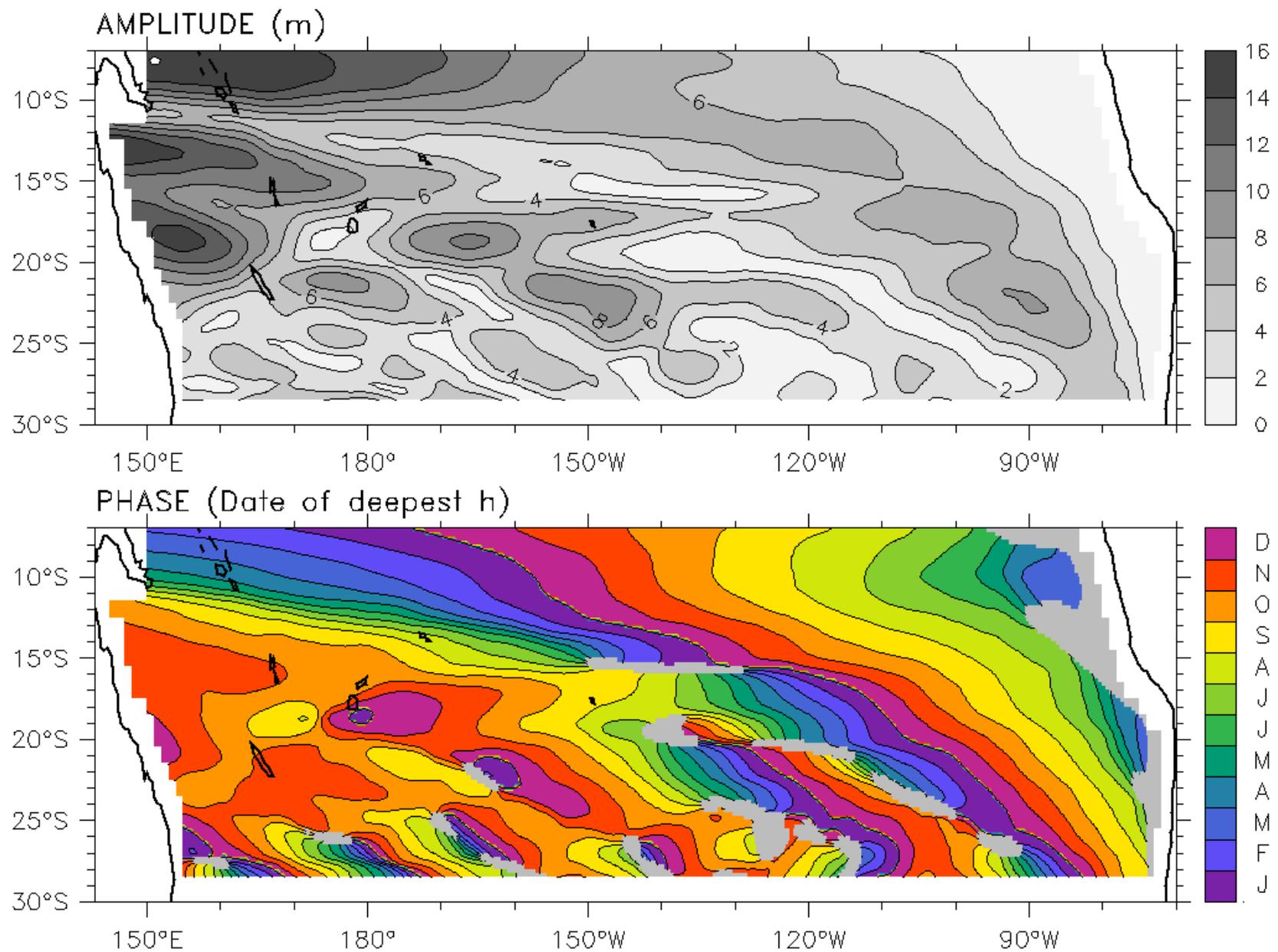
$h = \text{Curl}(\tau/f\rho)/(i\omega - c_r/L)$ . ERS winds 1 cpy.  $c_k = 3.5 \text{ m s}^{-1}$ ,  $L = 9000 \text{ km}$



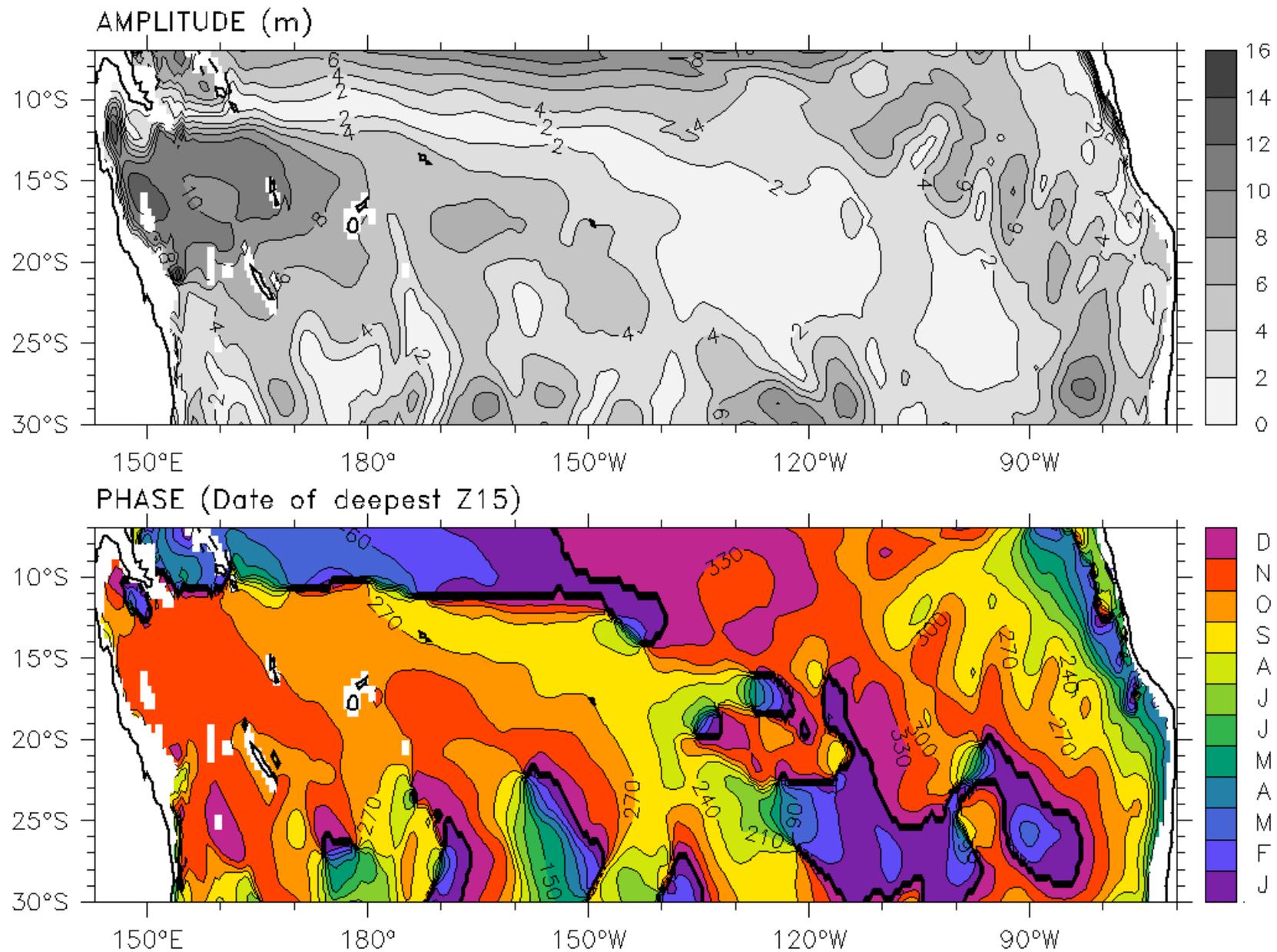
$$\alpha = \omega L / c_r \quad 1/(i\omega - c_r/L) = -(1+i\alpha)/(\omega(\alpha+1/\alpha))$$

$$\text{Lag} = \tan^{-1}(\alpha). \quad \text{Magnitude} = \text{Curl}(\tau/f\rho)[(1+\alpha)^{1/2}/\omega(\alpha+1/\alpha)]$$

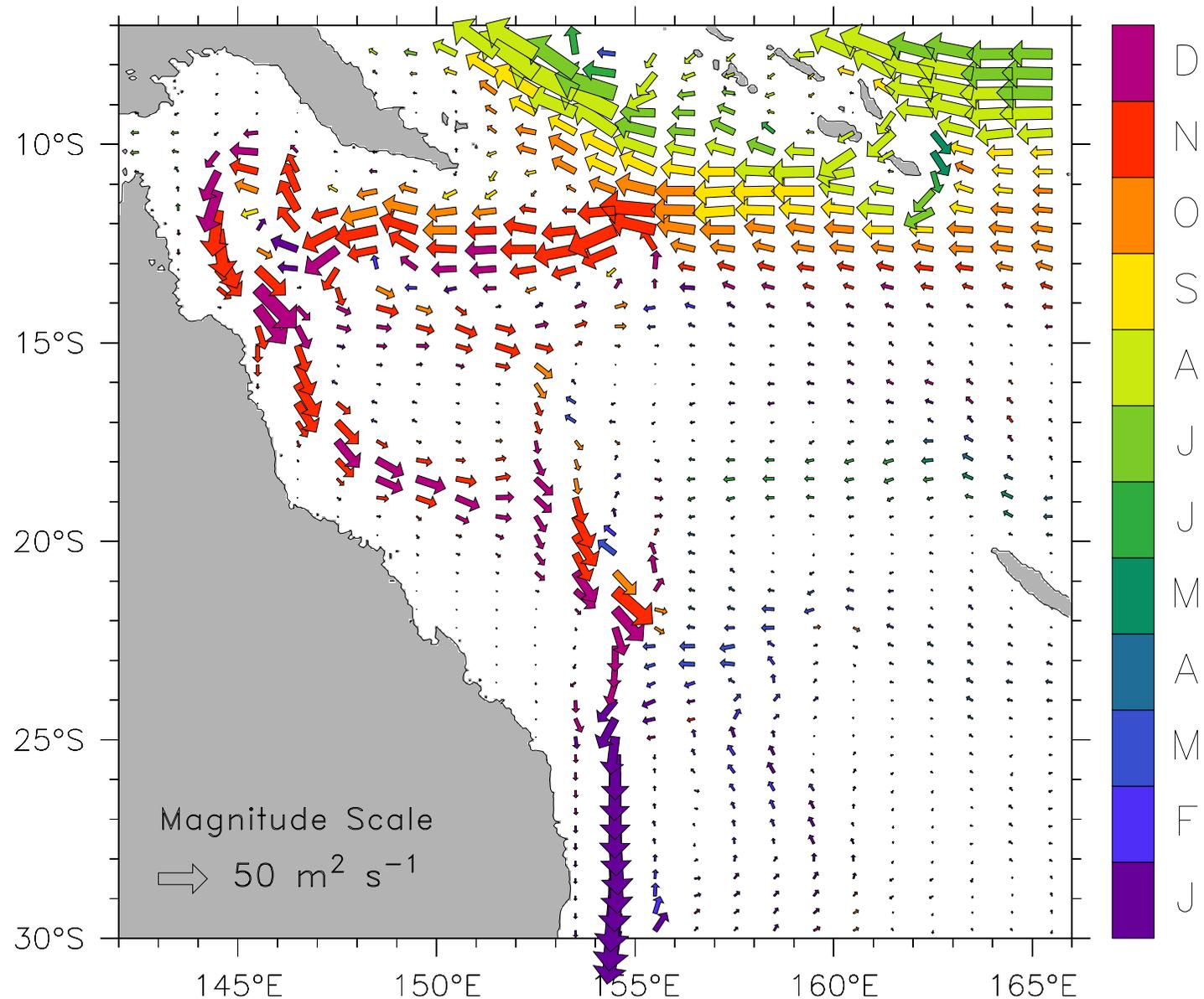
# 1 cpy harmonic of Rossby model h (real winds)



# 1 cpy harmonic of OGCM 15°C depth



# The annual cycle is a spinup and spindown of the gyre



D N O S A J J M A M F J

The wind-driven changes are a shoaling of the gyre in the 1st half of the year, and a deepening in the 2nd.

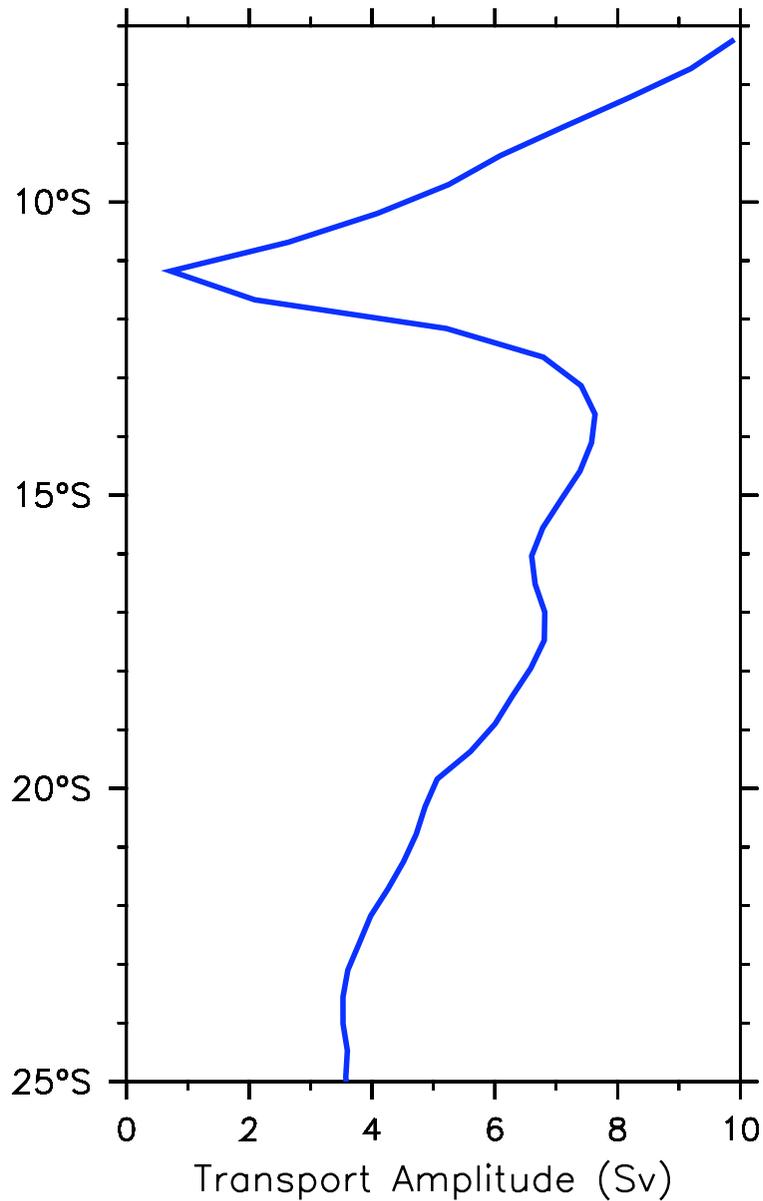
The resulting transport anomalies are alternately clockwise (spindown) and anticlockwise, but the tropical side is much stronger.

The OGCM solution shows that this also describes the western boundary changes.

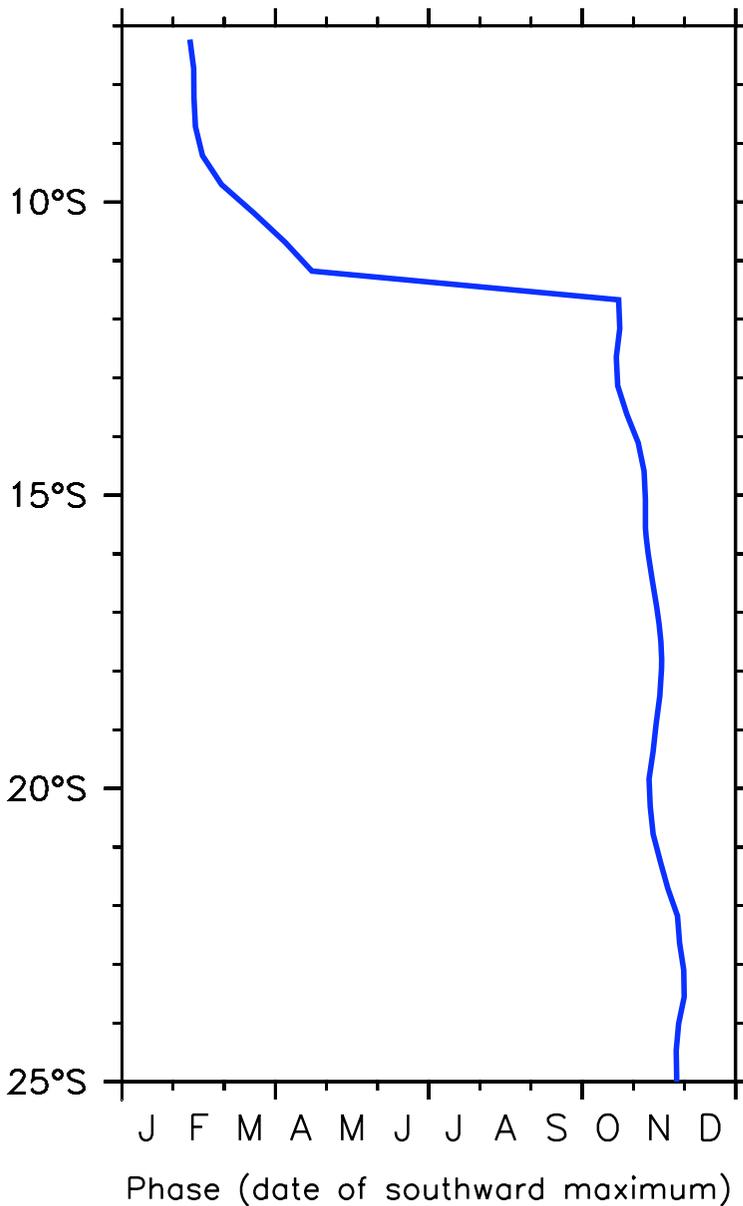
# ORCA model

1 cpy harmonic  
of WBC  
transport

## Amplitude



## Phase



← Phase shift (11°S)

# Deducing western boundary current anomalies from the interior Rossby solution

- By its neglect of velocity acceleration terms, the long Rossby model explicitly excludes western boundary dynamics.
- However, an evaluation can be made by balancing the incoming zonal transport of arriving Rossby waves (Godfrey 1975, Appendix B.2):

In the reduced gravity system, the WBC transport anomaly is:

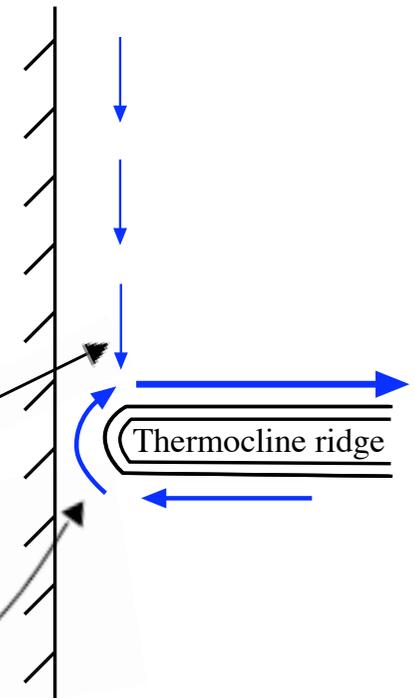
$$V(y) = V_S - \int_{y_S}^y u_{RW} dy' = V_S + \int_{y_S}^y \frac{c^2}{f} \frac{\partial h_{RW}}{\partial y'} dy'$$

$$= V_S + c^2 \left( \frac{h_{RW}(y)}{f} - \frac{h_{RW}(y_S)}{f_S} + \int_{y_S}^y \frac{\beta}{f^2} h_{RW} dy' \right)$$

Direct effect of Rossby h-field

Constant term. Cancels at  $y_S$

$\beta$ -term. Mismatch of  $u_{RW}$

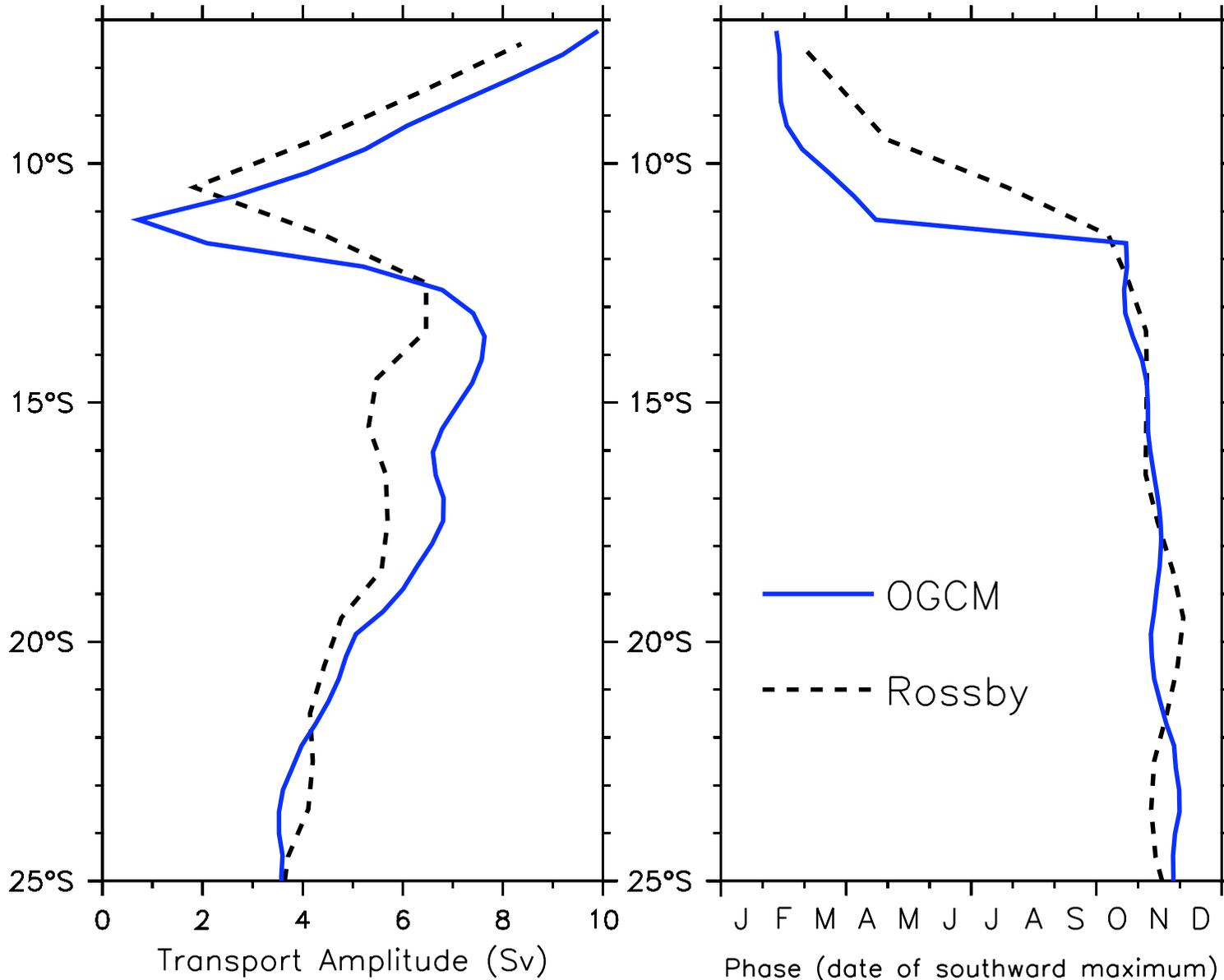


# Compare Rossby model

1 cpy harmonic  
of WBC  
transport

## Amplitude

## Phase



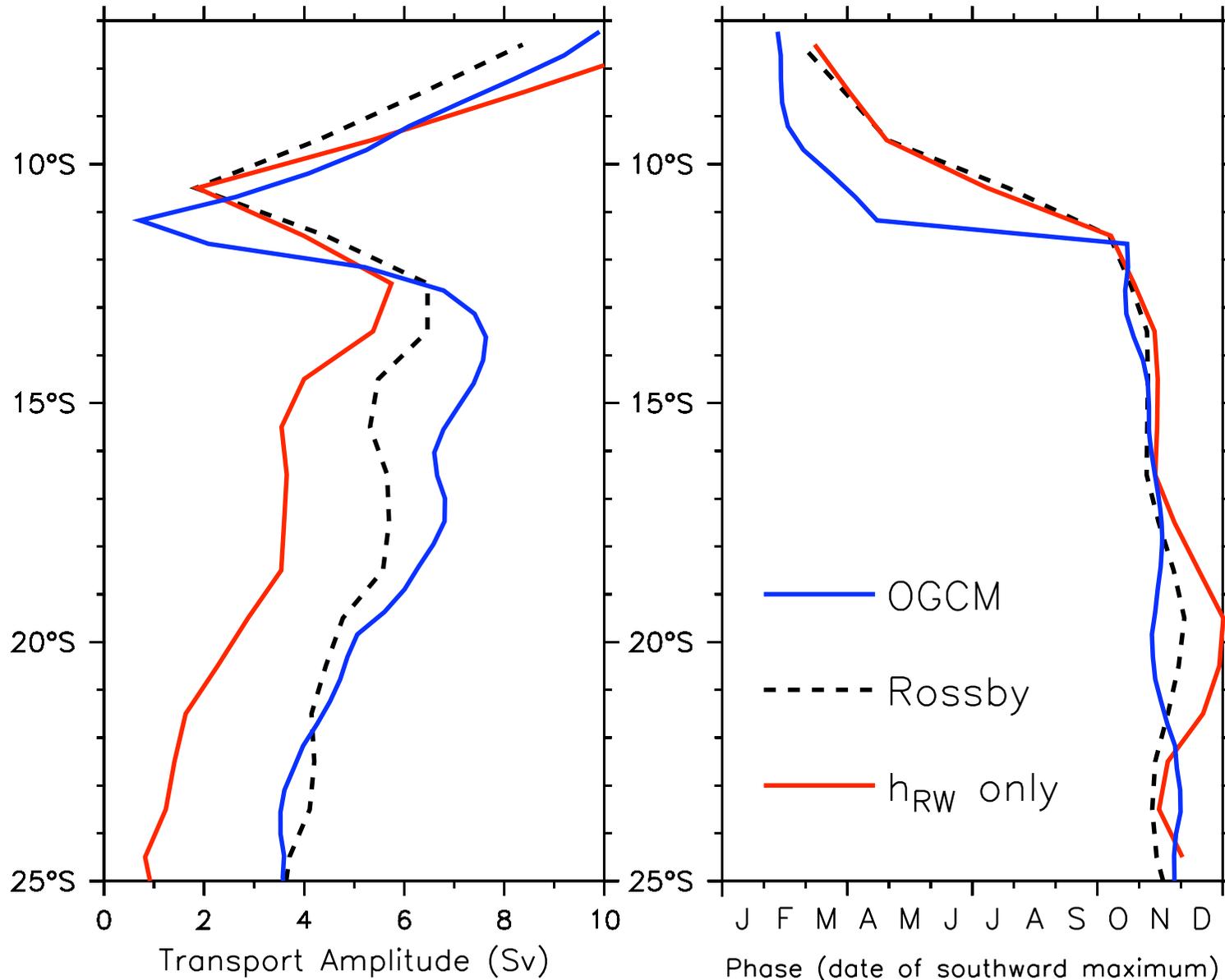
The 11°S phase shift is found in the Rossby solution, though it excludes western boundary dynamics and “knows” about the continent only from the 25°S boundary condition.

# Compare Rossby model: direct effect only

1 cpy harmonic  
of WBC  
transport

## Amplitude

## Phase

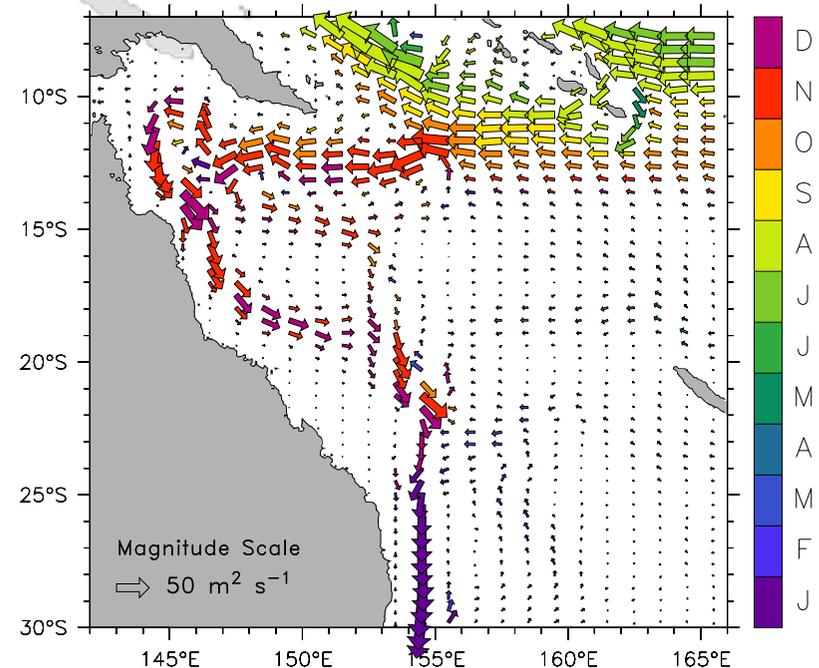


The structure of the solution is primarily in the direct effect of the interior Rossby height field.

The remainder:  
1) 25°S B.C.  
2)  $\beta$ -term (Godfrey)

## Conclude:

- A linear Rossby model represents much of the annual variability in the subtropical South Pacific. The interior of the gyre heaves in a standing oscillation, driven by strong wind variations in the west.
- WBCs along the entire east coast of Australia fluctuate coherently. The linear model is also useful for interpreting WBC variability.
- The out of phase WBC across  $11^{\circ}\text{S}$  is due to interior winds, not to boundary dynamics or the shape of the coast.
- The bifurcation latitude is meaningless with respect to annual transport from the South Pacific subtropical gyre to the equator. What about the North Pacific?
- The OGCM predicts the occurrence of annual WBCs on the deep east flanks of the Queensland Plateau and the Solomon Islands.

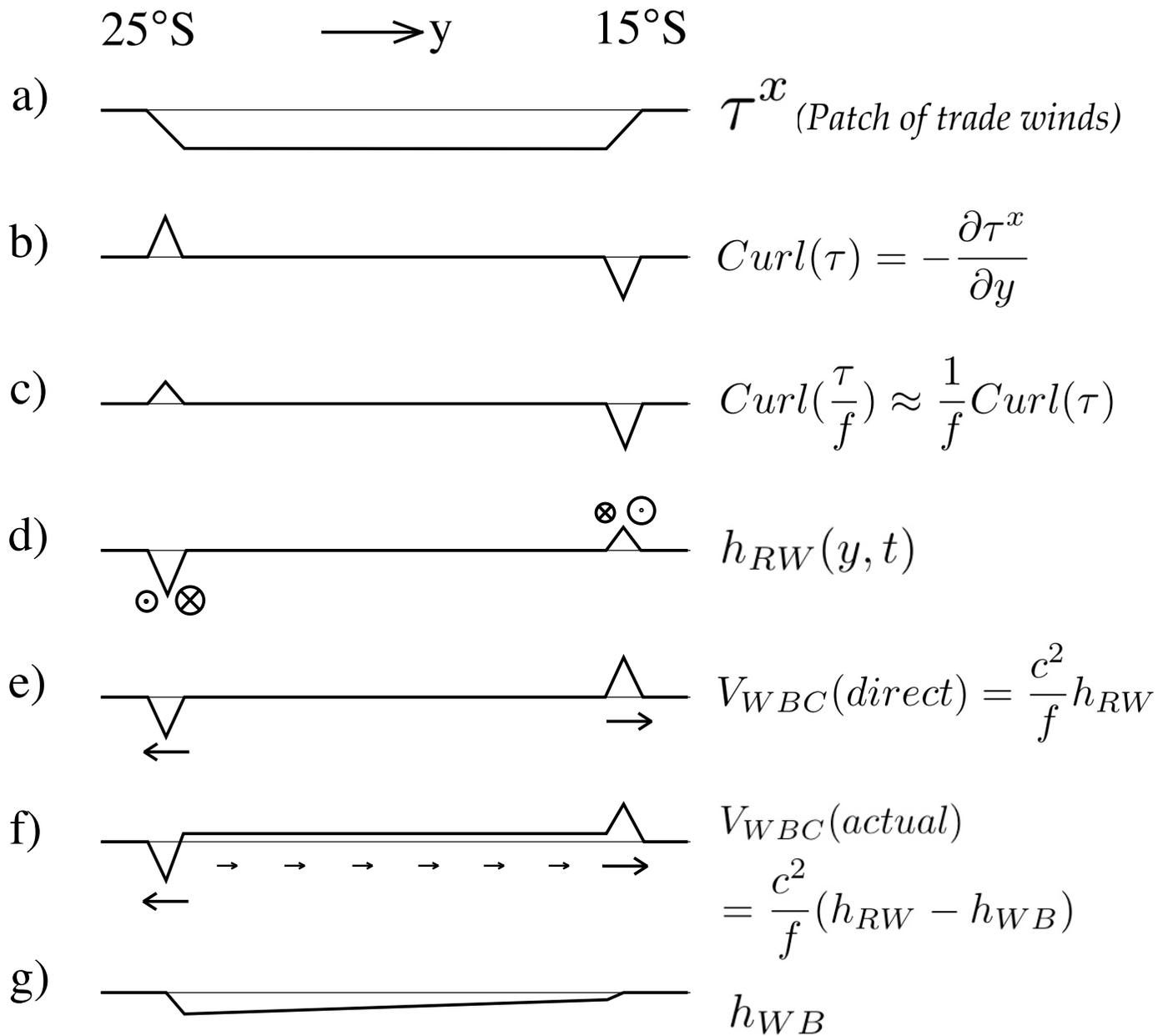


**Extra**

**Figures**

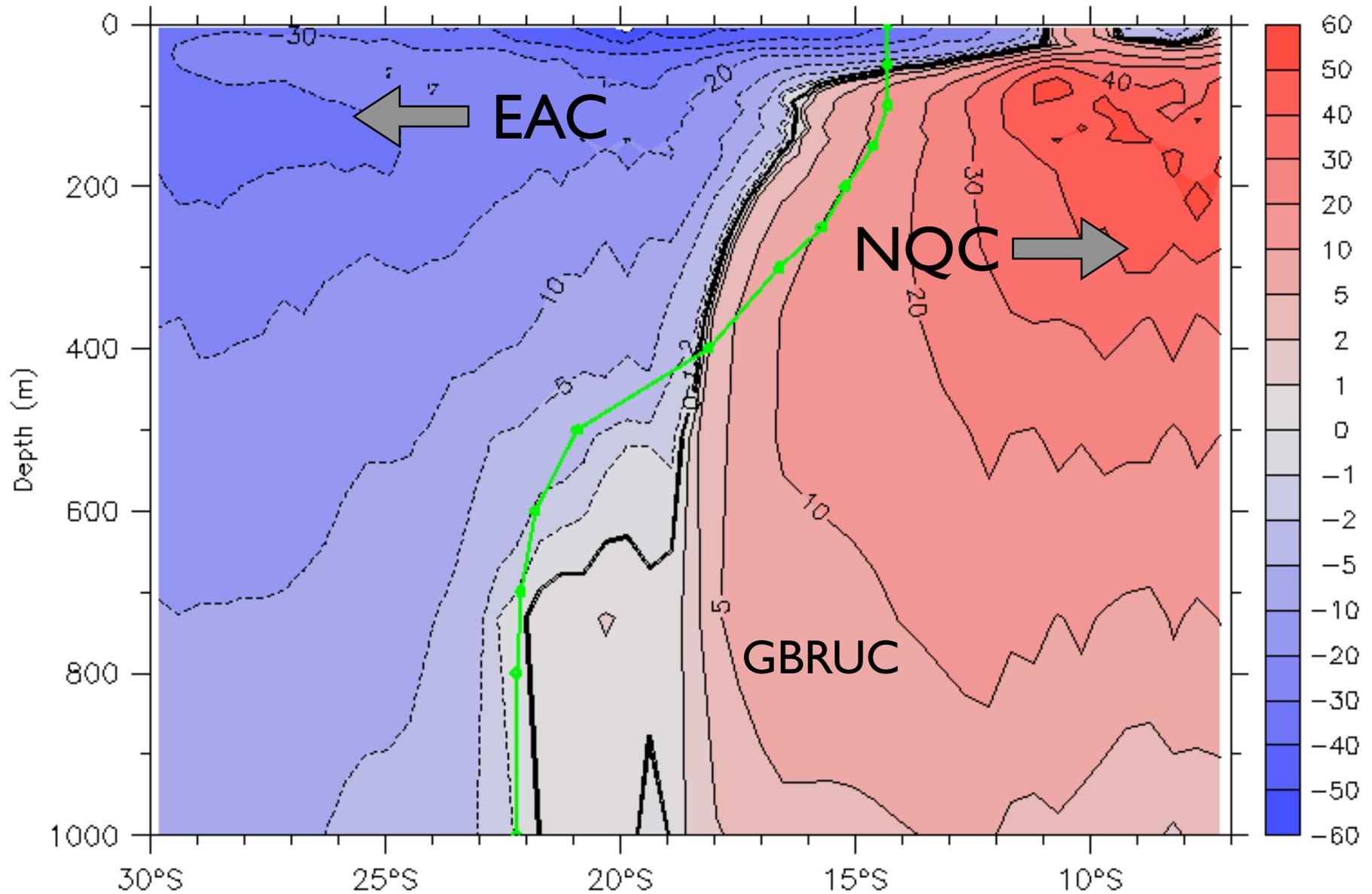
**Follow**

Godfrey WBC due to incoming Rossby waves. Longshore pressure gradient within the western BL balances boundary friction.

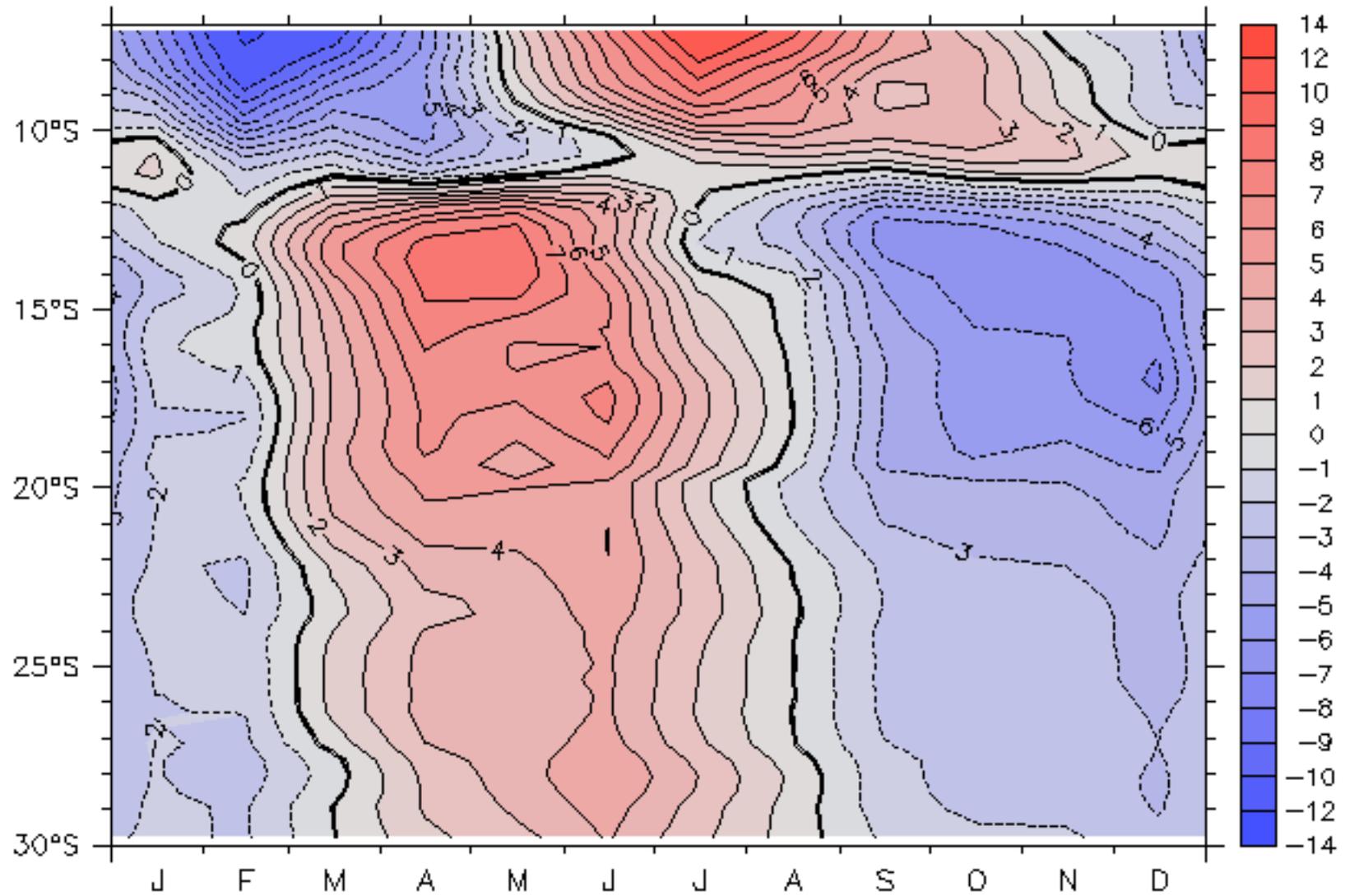


# Mean model western boundary current

Green line is bifurcation from CARS data

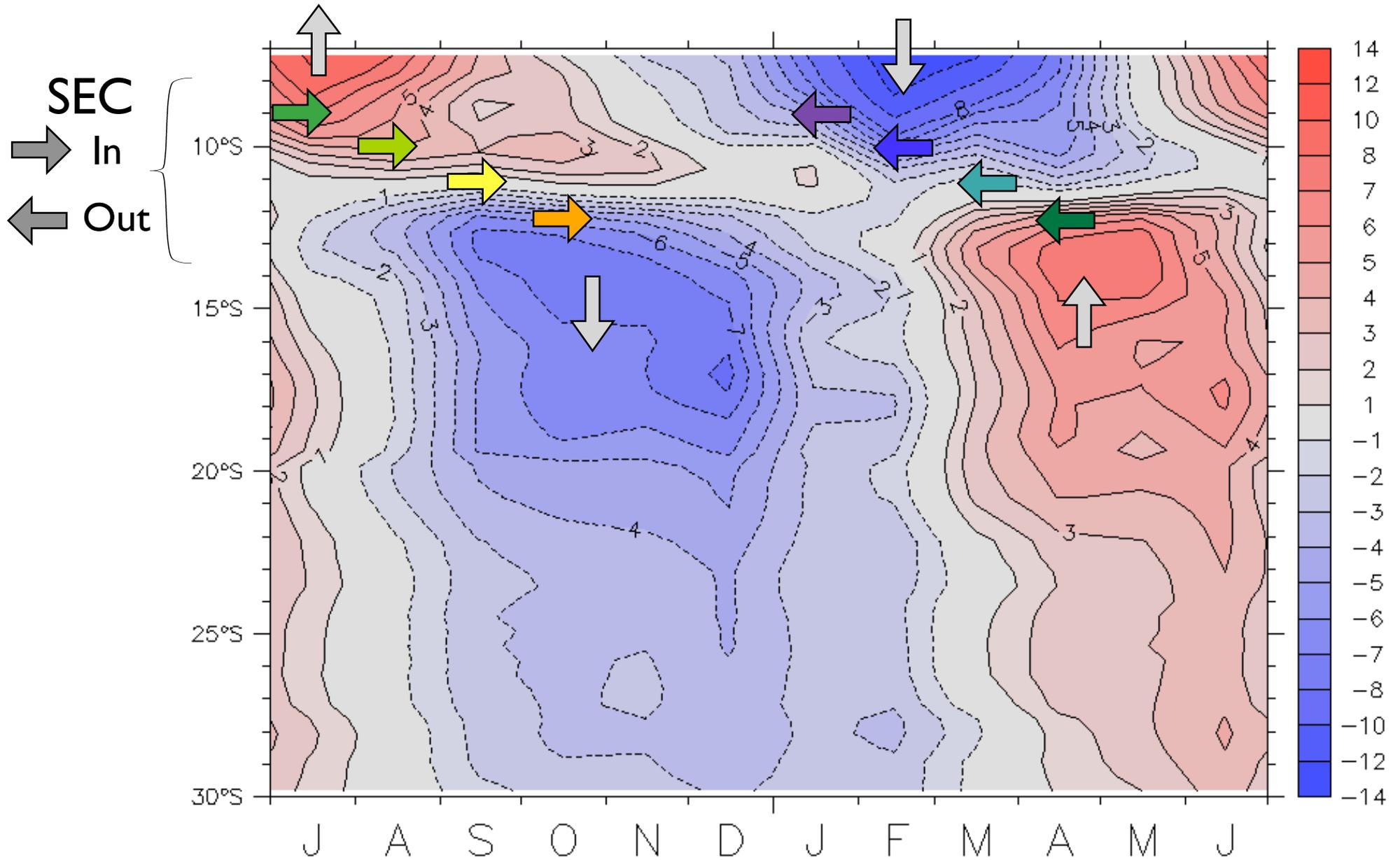


# ORCA seasonal WBC transport anomalies (Sv)



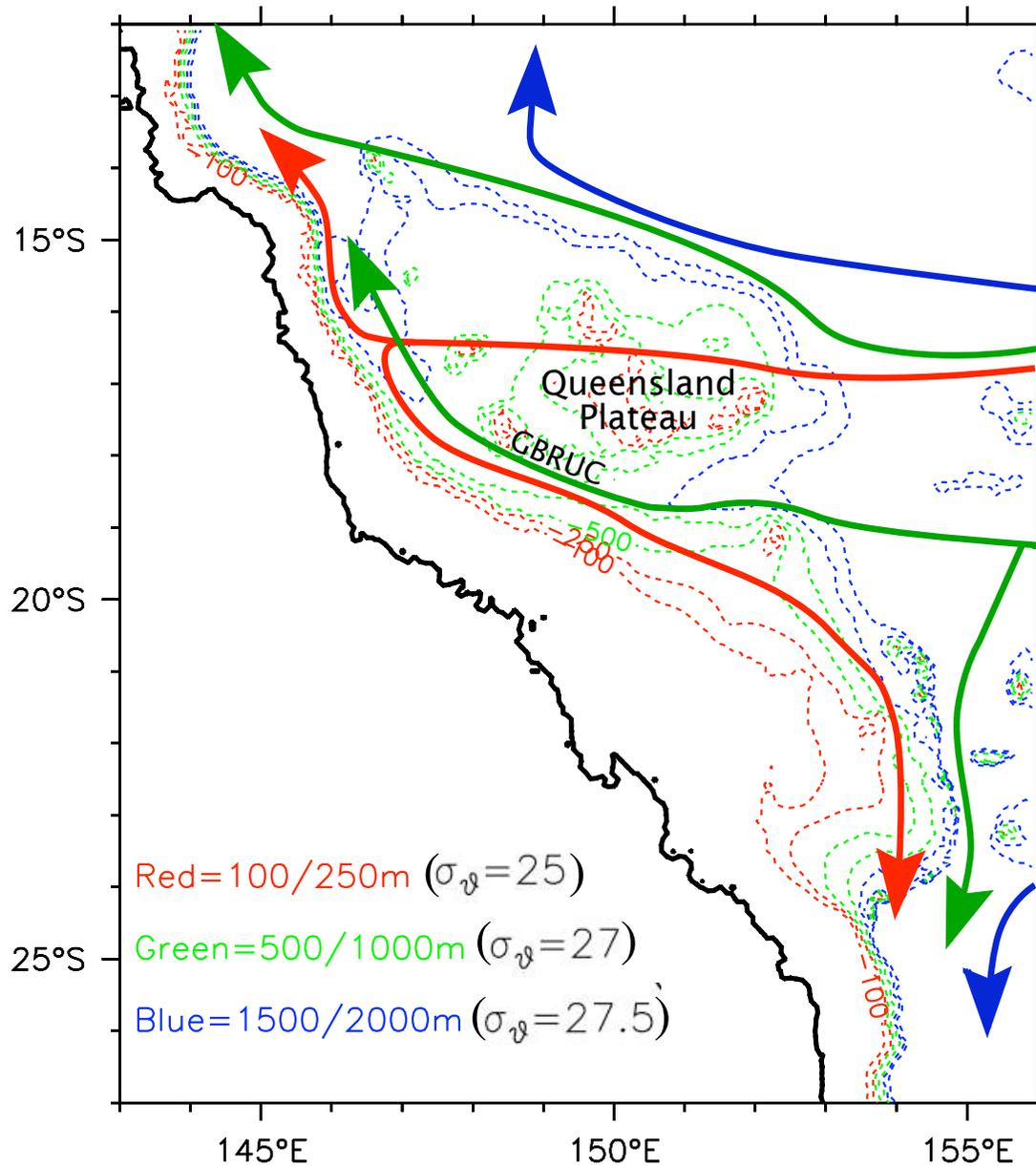
# Western boundary transport (Sv)

In relation to SEC inflow



# Great Barrier Reef Bathymetry

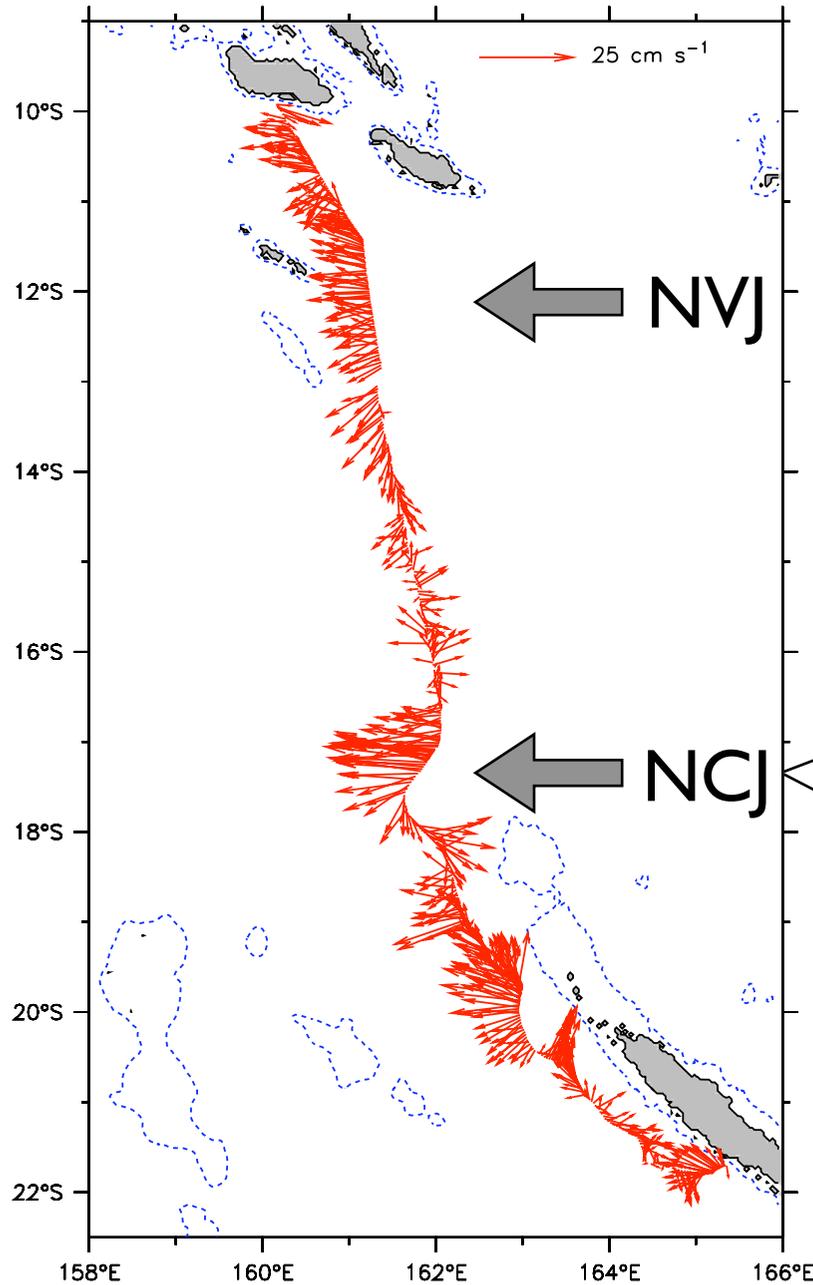
Arrows show pathways at density levels



The Queensland Plateau greatly complicates description or diagnosis of the bifurcation!

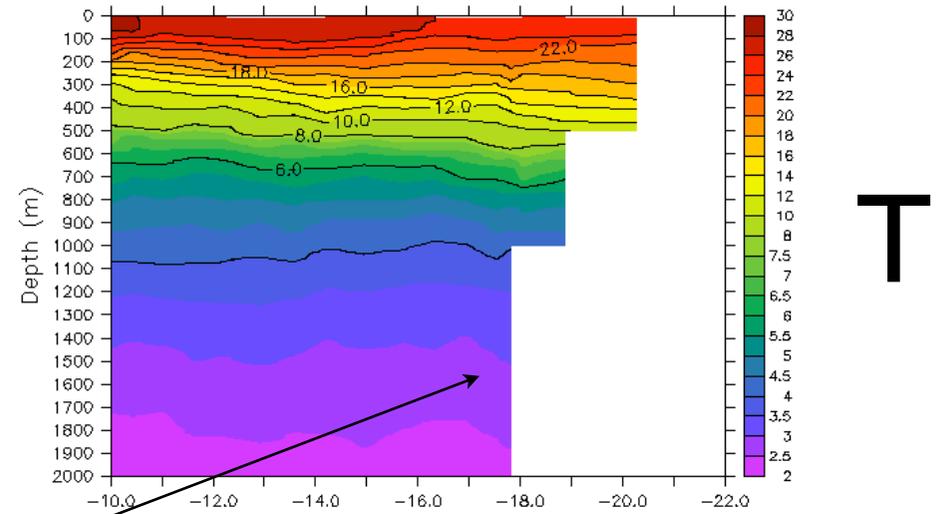
# Currents along glider track

Average currents over 0–600m

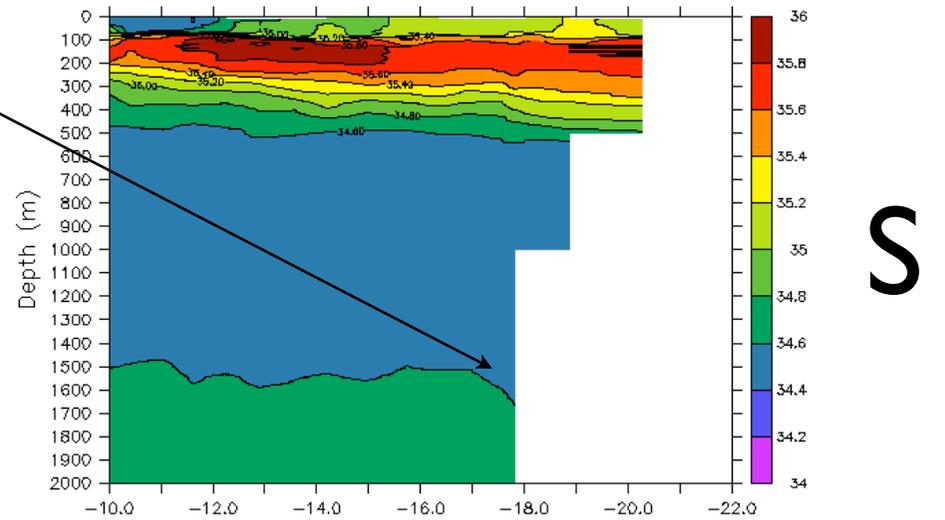


Coast and 500m isobath drawn

# The NCJ extends very deep! Sections during July–Oct 2005



Temperature CTD Secalis 3

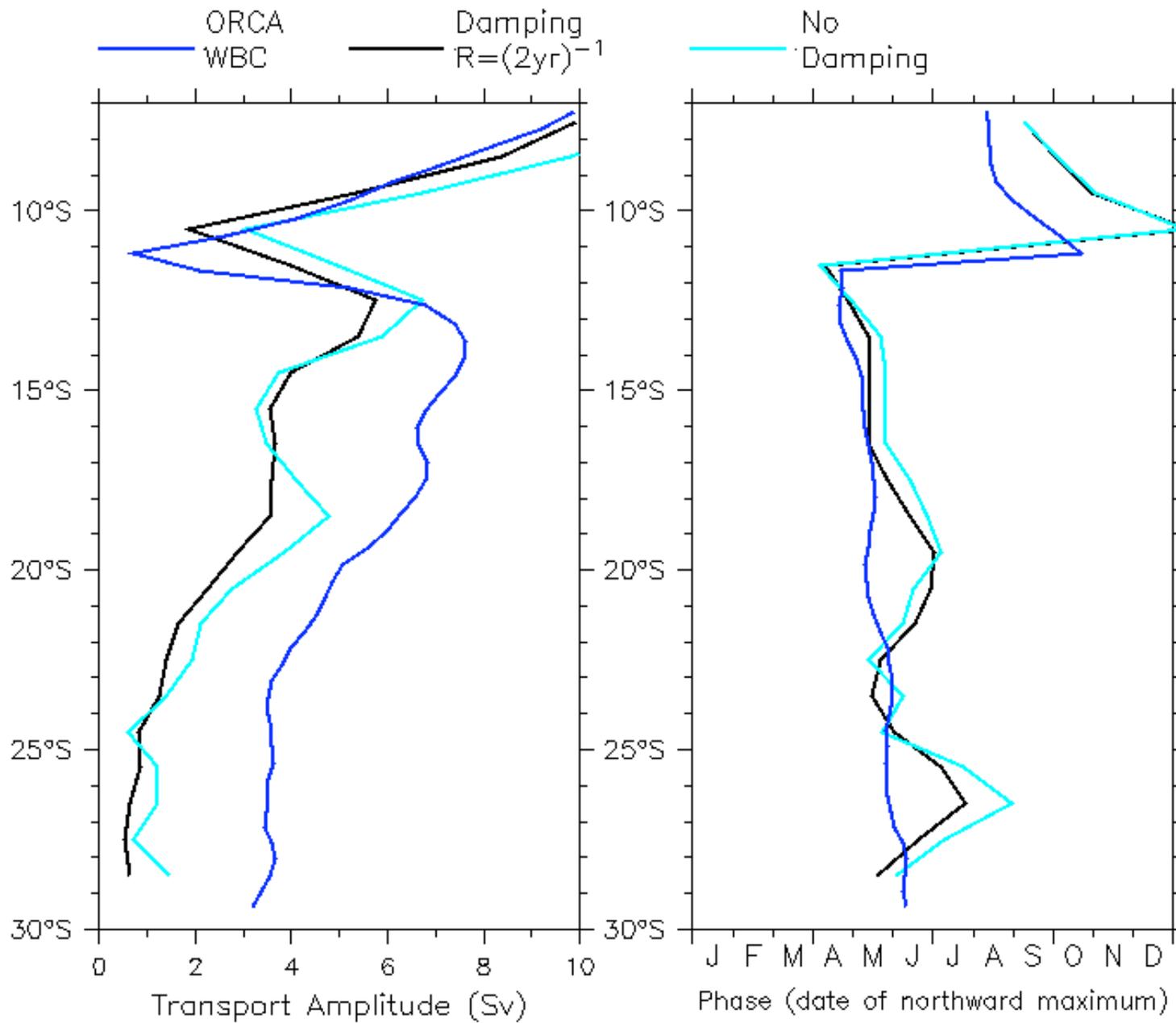


Salinity CTD Secalis 3

T

S

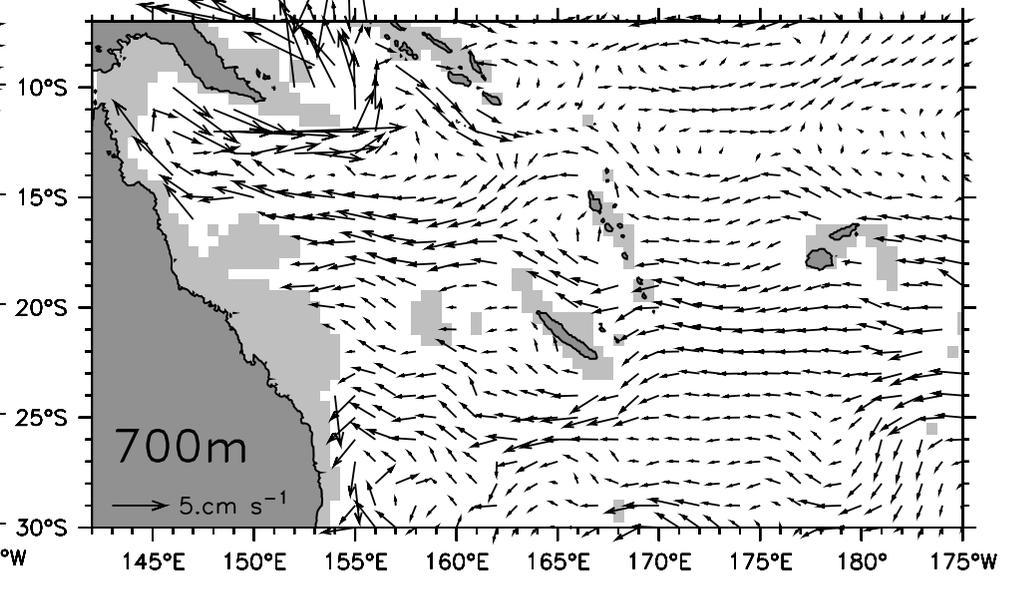
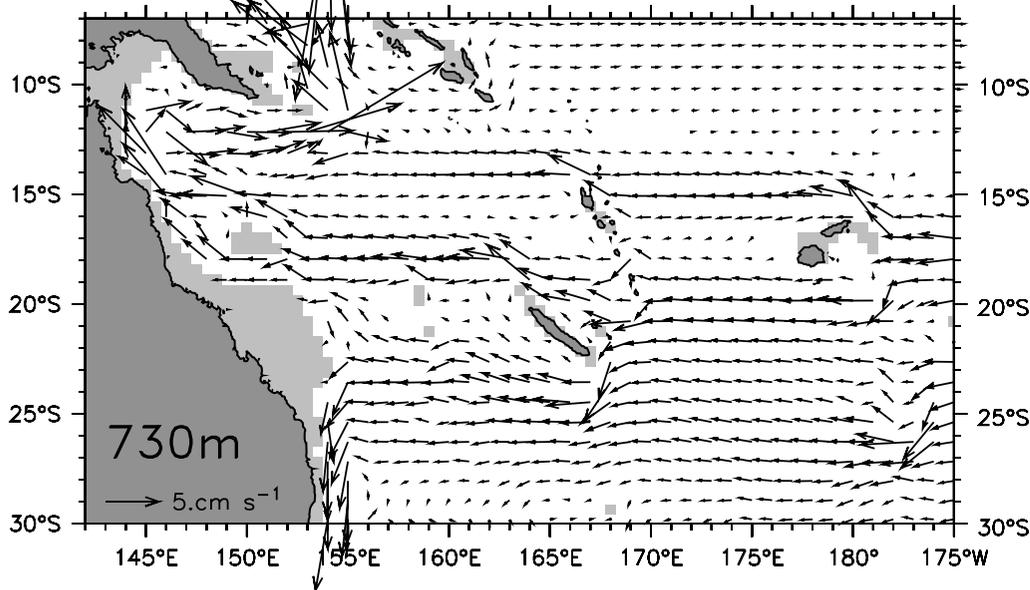
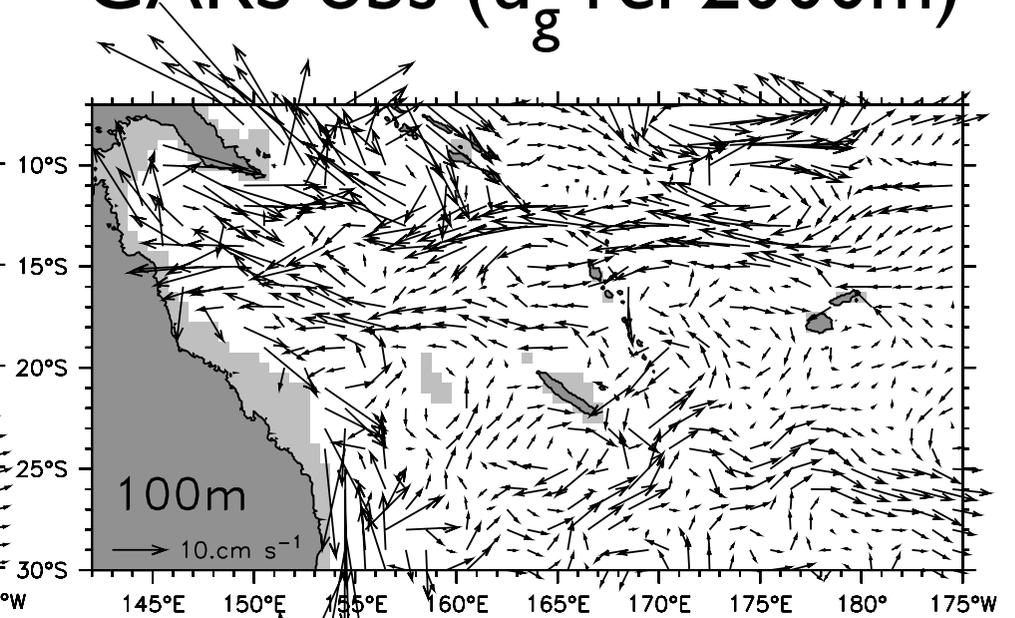
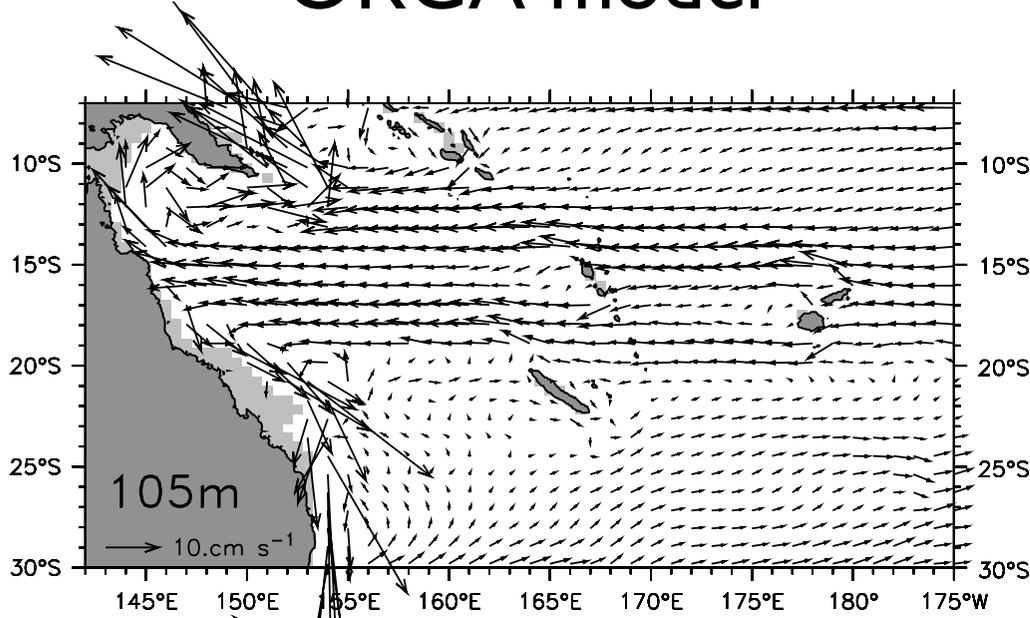
# Rossby solution: effect of damping term



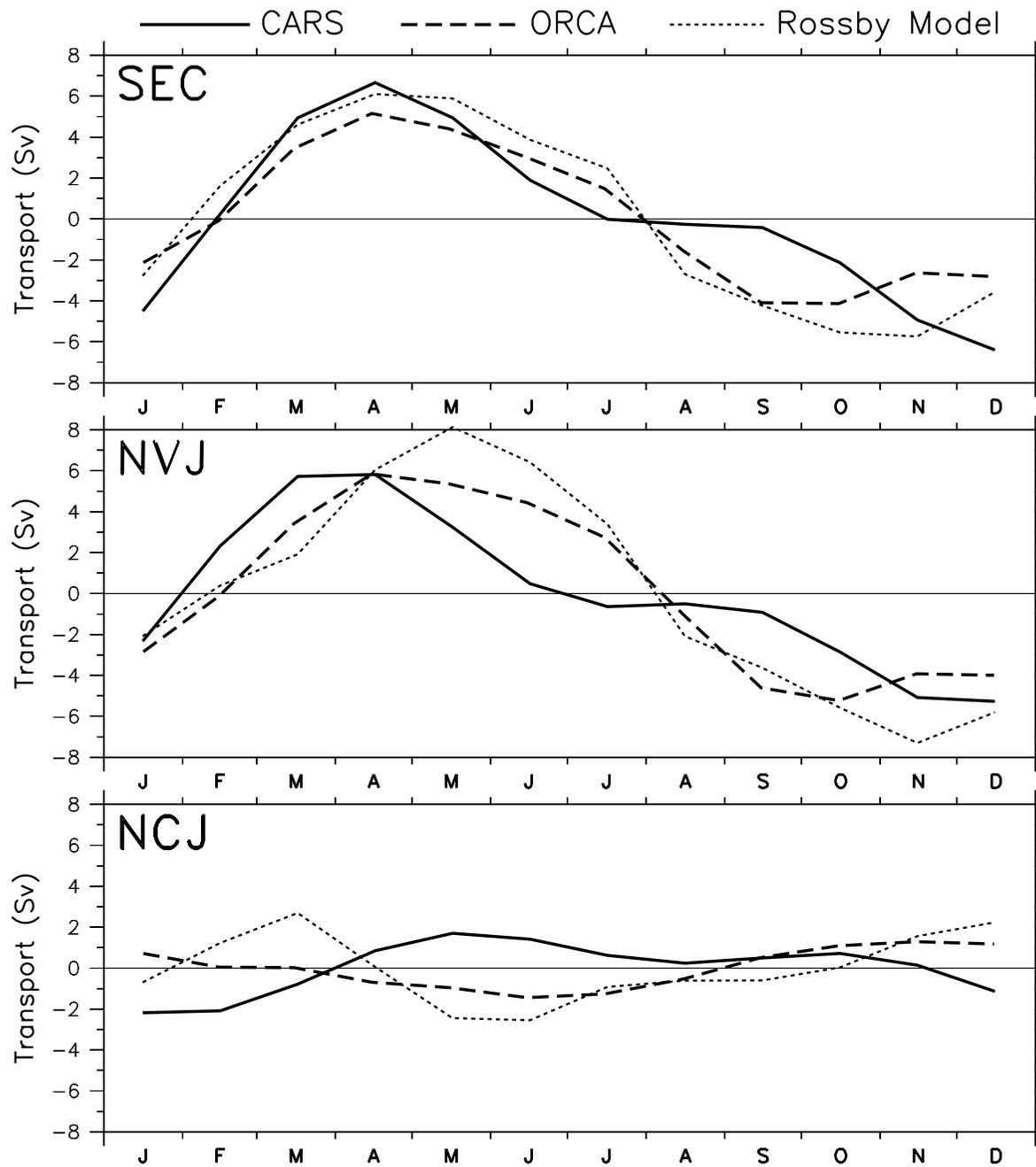
# Compare ORCA and CARS currents

## ORCA model

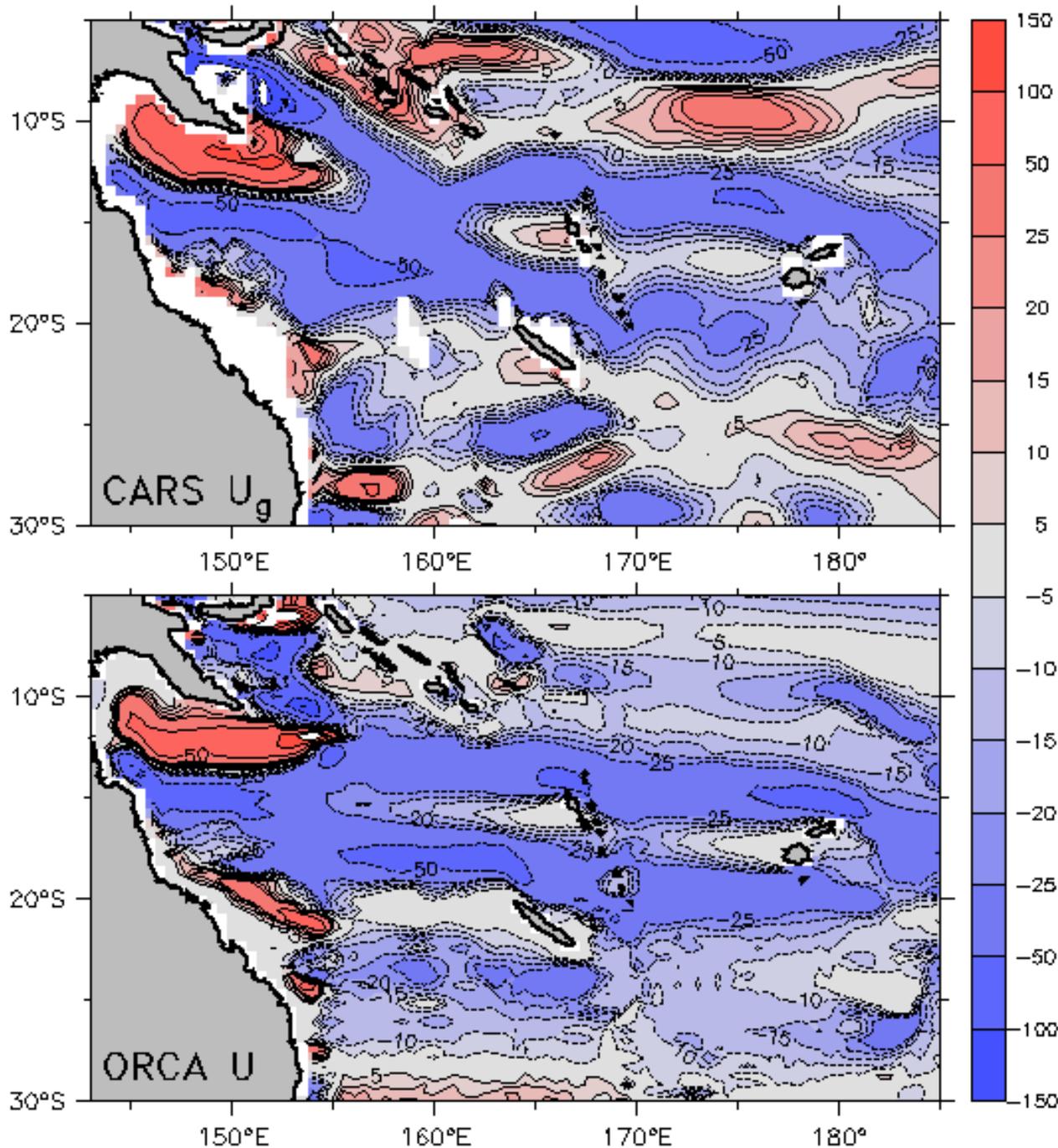
## CARS obs ( $u_g$ rel 2000m)



# Transport at 162.5°E



# ORCA and CARS zonal transport



0-2000m transport

CARS =  $u_g$  rel 2000m

ORCA = total  $u > 2000\text{m}$   
( $\text{m}^2 \text{s}^{-1}$ )

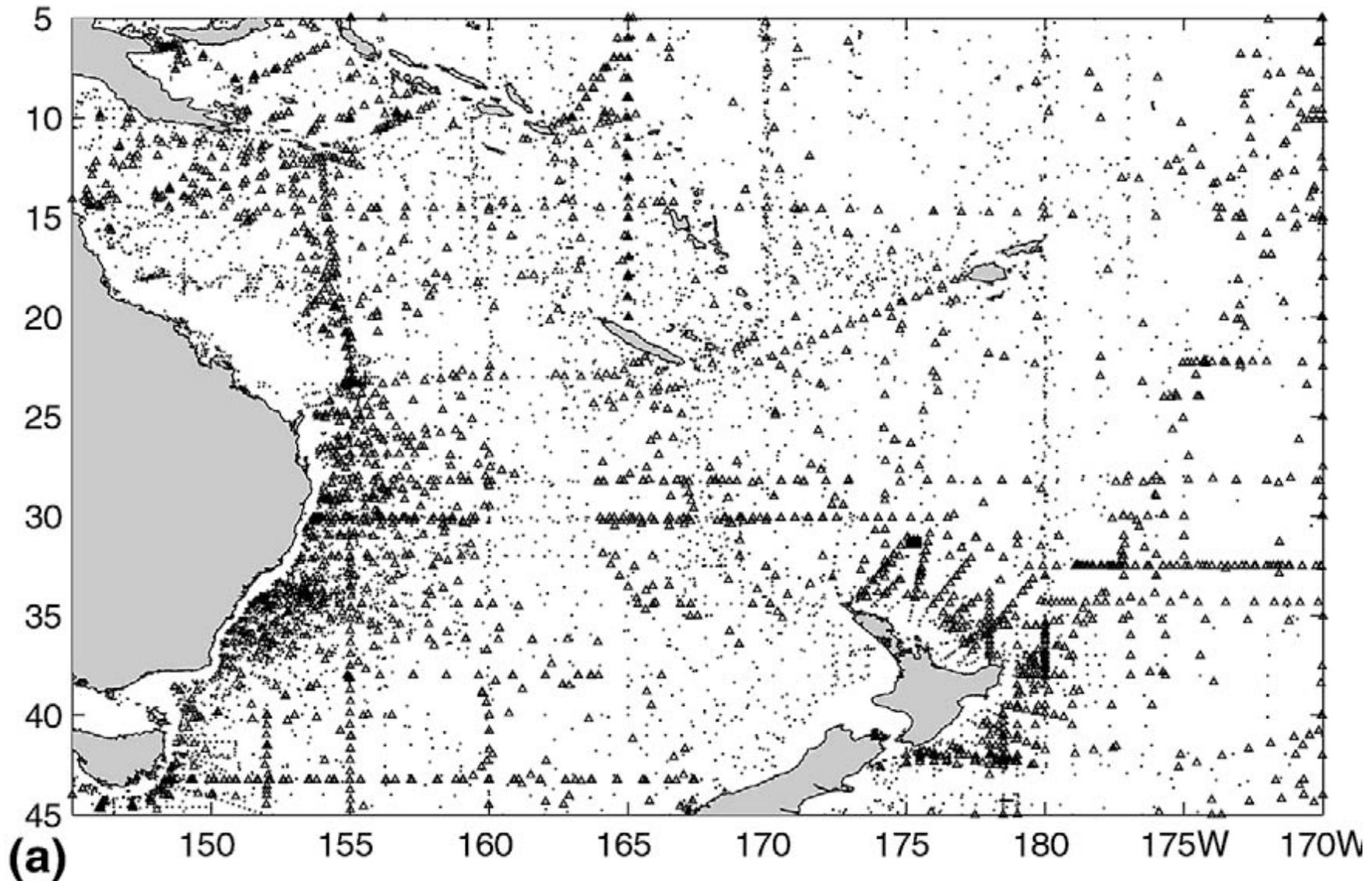
CARS is a new  
CSIRO CTD  
compilation for  
the S Pacific and  
S Indian Oceans  
Ridgway & Dunn (2003)



# Available T/S profiles (CARS climatology)

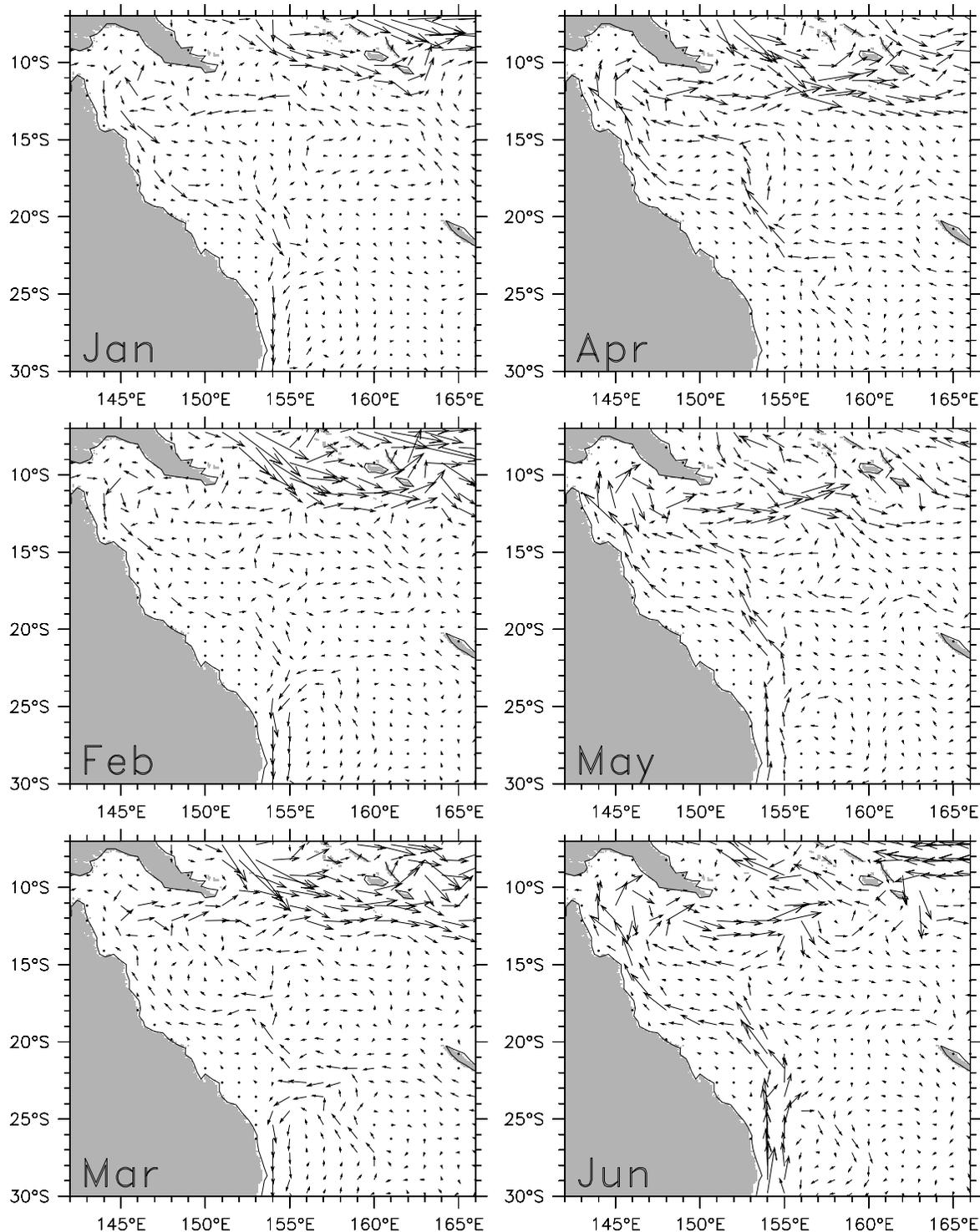
*K.R. Ridgway, J.R. Dunn / Progress in Oceanography 56 (2003) 189–222*

Dots > 500m; Triangles > 2000m



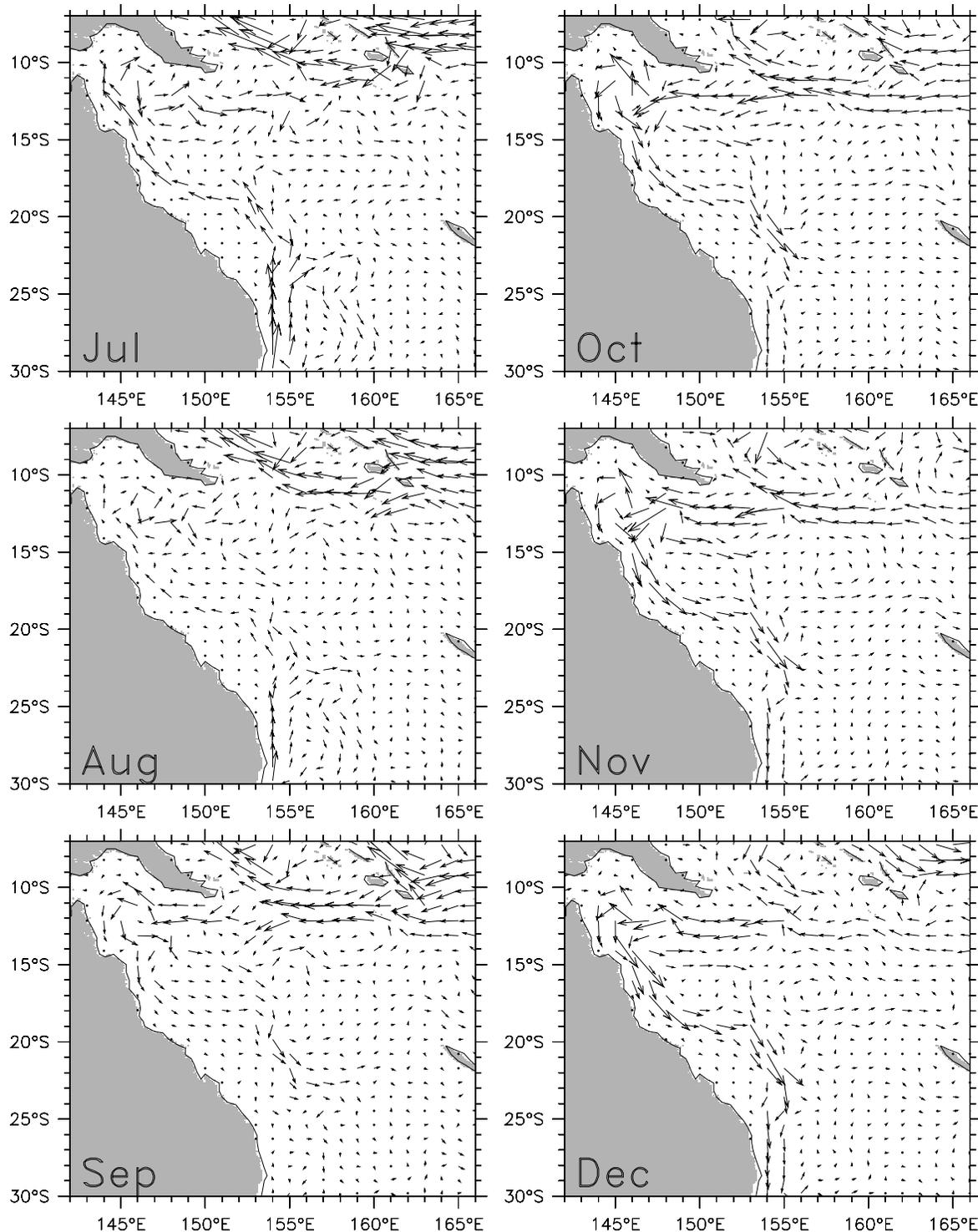
0-2060m transport  
Jan-Jun climatology.

(No filtering;  
Not a harmonic;  
Plain climatology.)

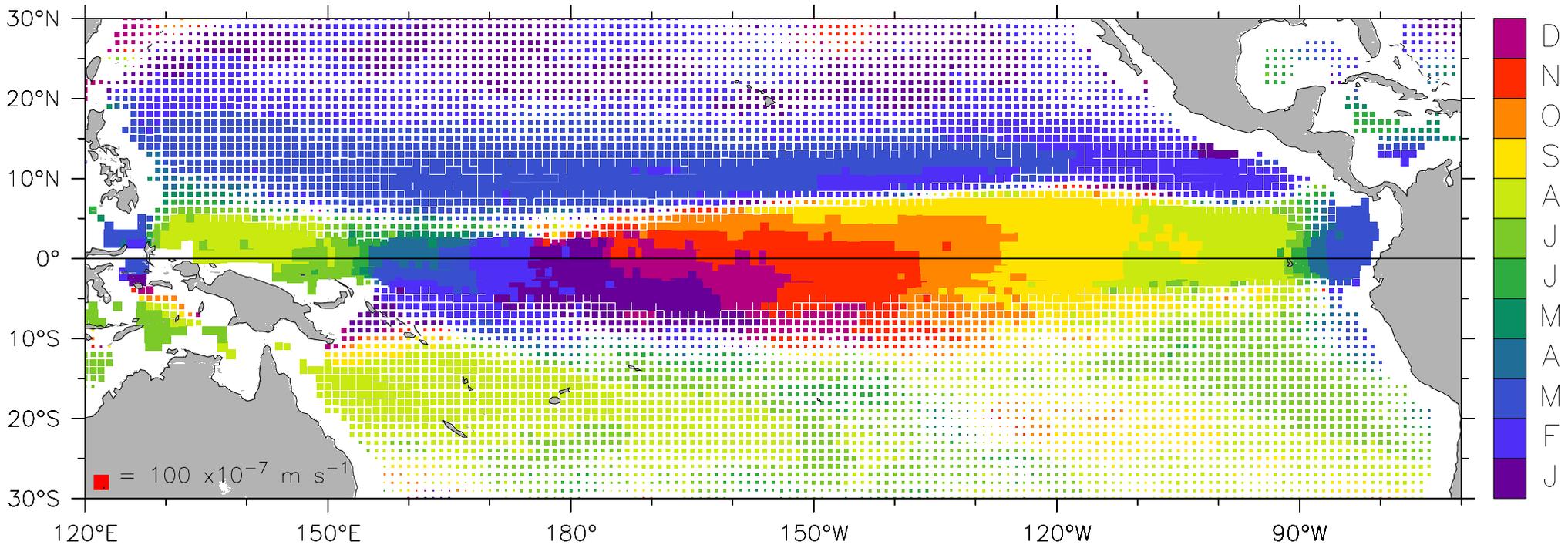


0-2060m transport  
Jul-Dec climatology.

(No filtering;  
Not a harmonic;  
Plain climatology.)

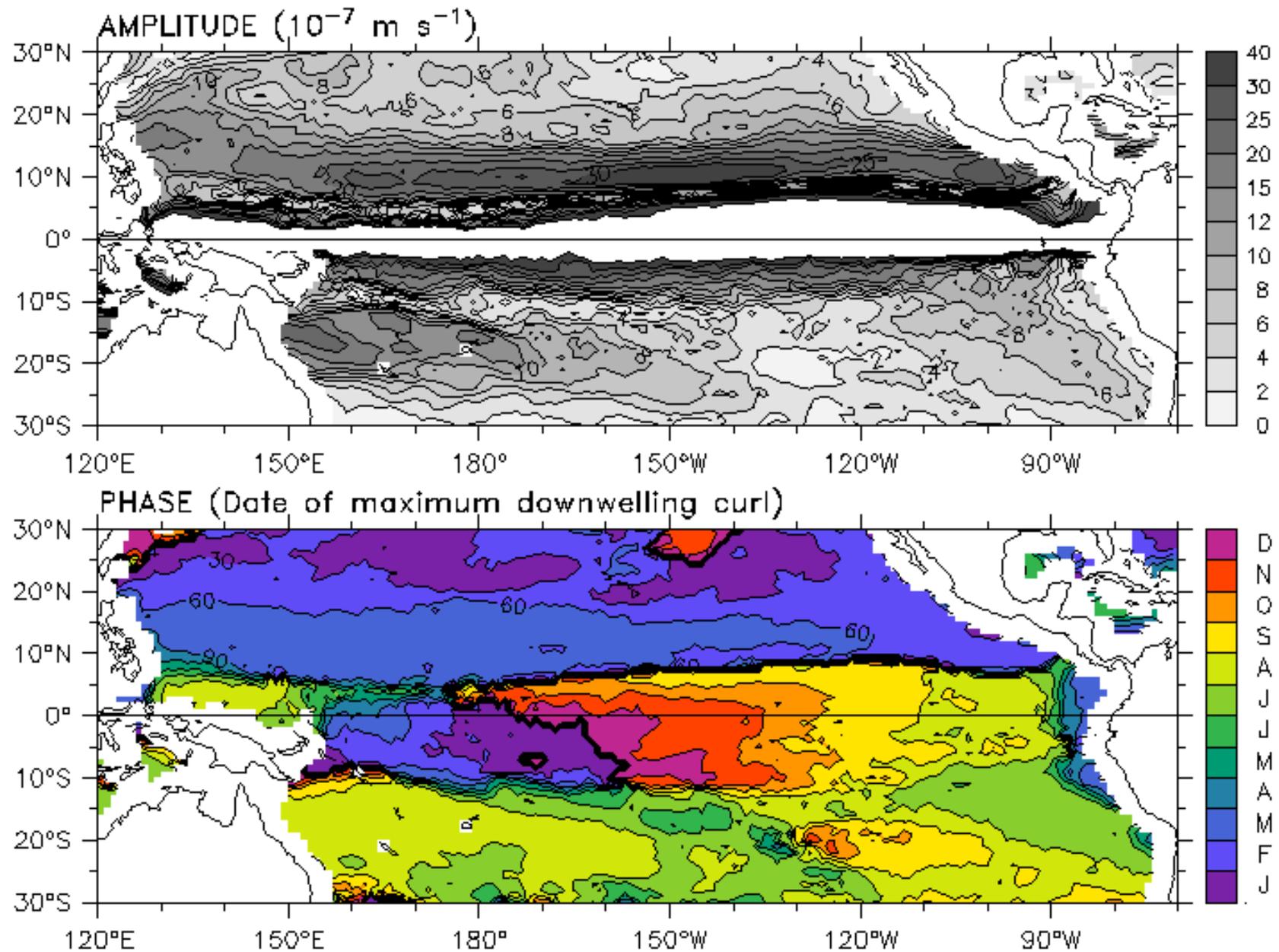


# 1 cpy harmonic of $Curl(\tau/f\rho)$



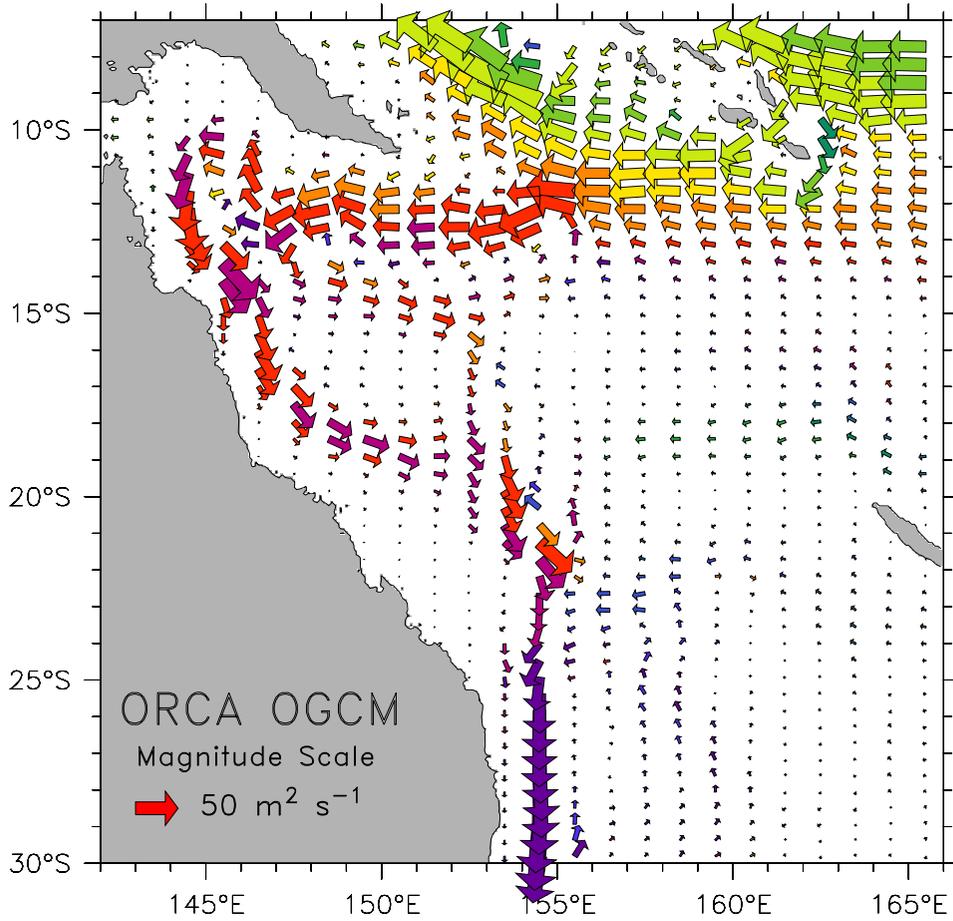
Area of square indicates amplitude (scale at lower left)  
Color of square indicates phase (month of maximum downwelling)

# 1 cpy harmonic of $Curl(\tau/f\rho)$

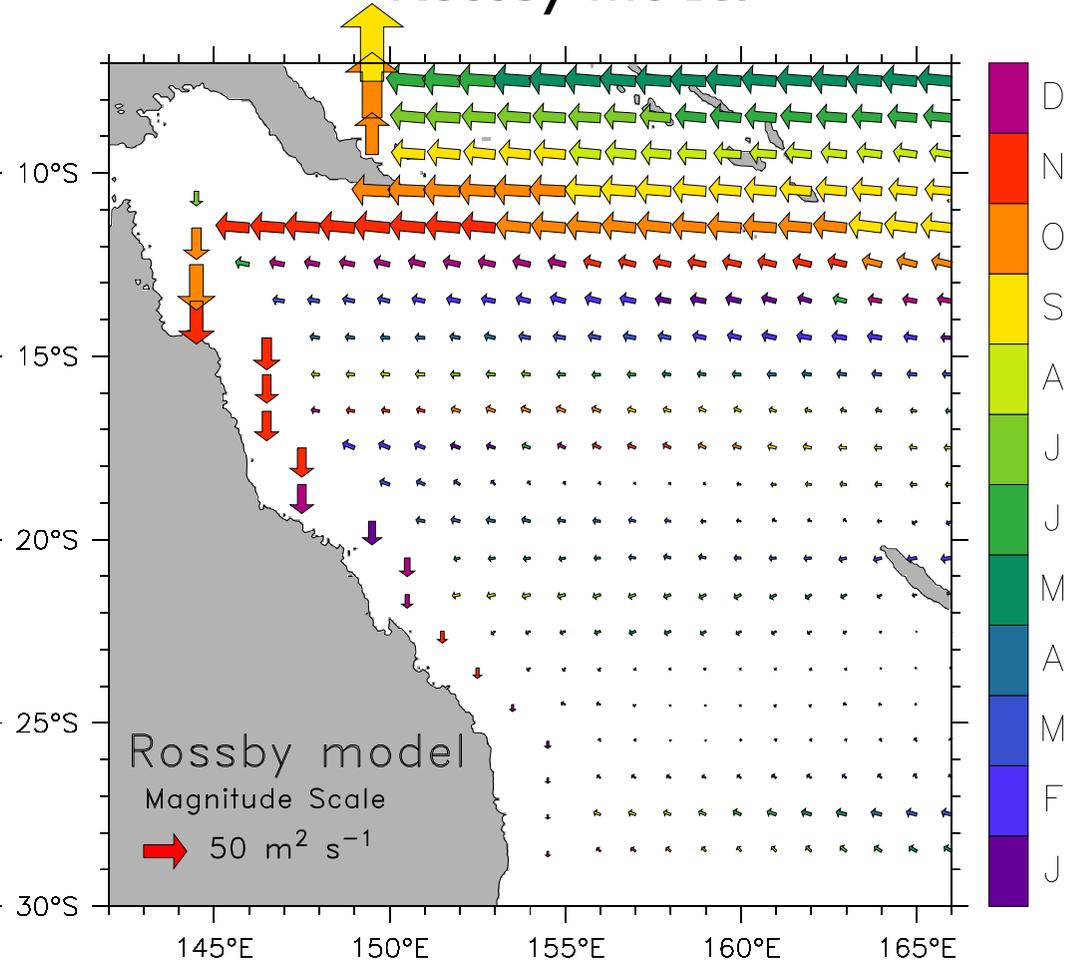


# 1 cpy harmonic of transport

## ORCA

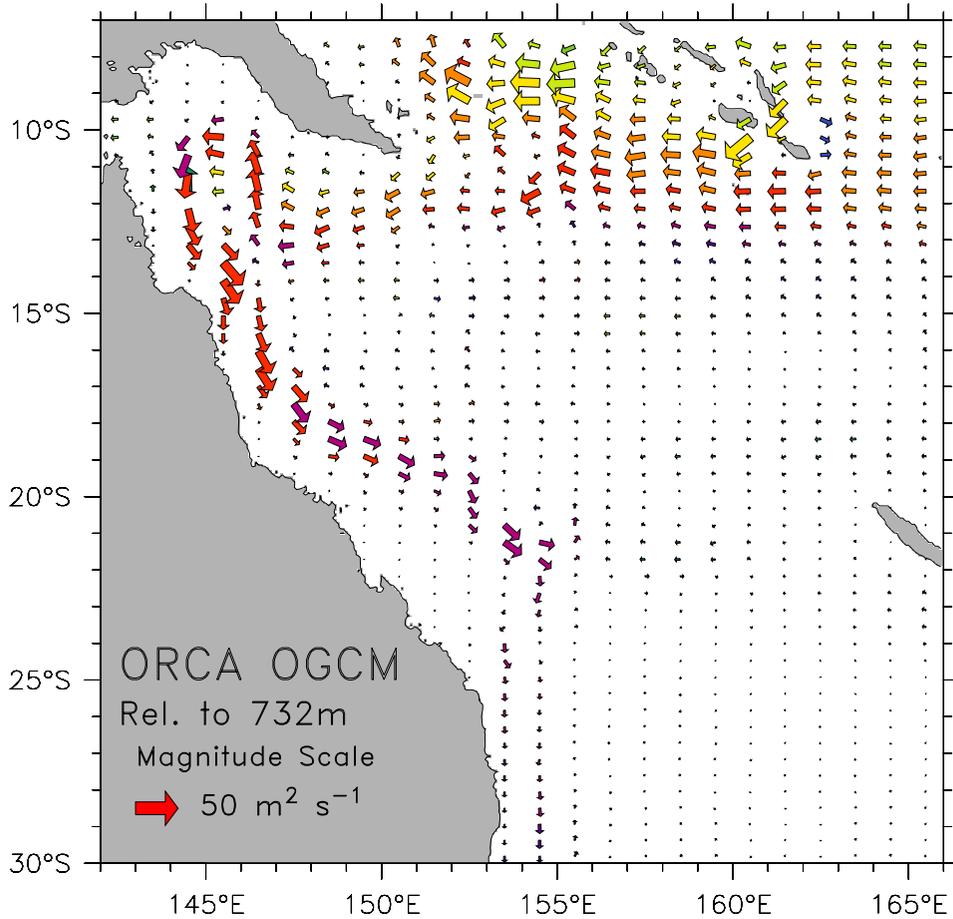


## Rossby model

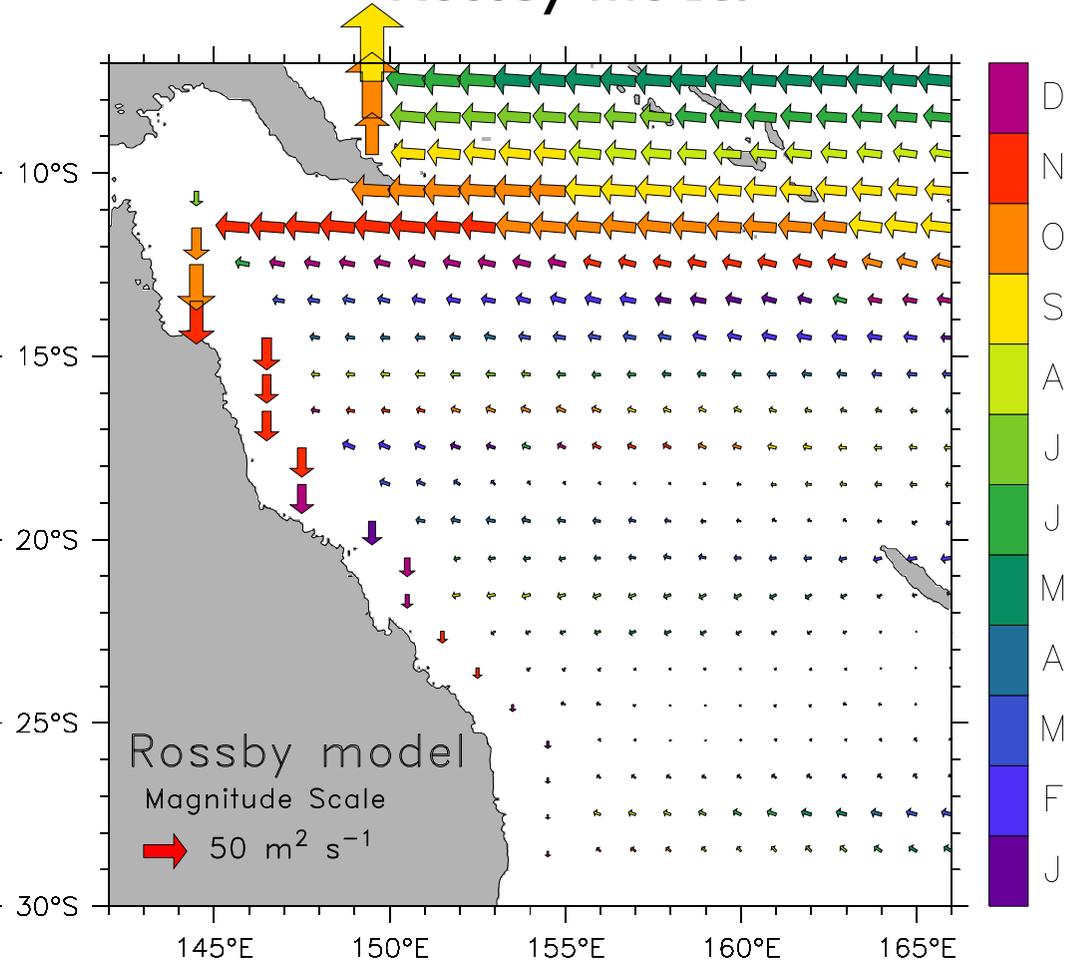


# 1 cpy harmonic of transport

## ORCA (rel 730m)



## Rossby model



# Variance ellipses for the annual cycle of ERS winds

RMS of ERS wind stress  
(Annual cycle)

